

A reprint from

American Scientist

the magazine of Sigma Xi, The Scientific Research Society

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What Creates Static Electricity?

Traditionally considered a physics problem, the answer is beginning to emerge from chemistry and other sciences

Meurig W. Williams

When two objects are brought into contact and then separated, electrical charges are generated at the surfaces. Such events are called *triboelectric* charges, also known as contact or static charges. Triboelectricity is one of the oldest areas of scientific study, dating back to experiments by the ancient Greek philosopher Thales of Miletus, who discovered that rubbing amber against wool led to electrostatic charging. Indeed, triboelectric in Greek means “rubbing amber”; however, rubbing is not necessary because such charging also results from simple nonfrictional contacts.

The buildup of this electrical potential can lead to electrostatic discharge, with consequences that can range from discomfort to disaster. Results can be as mild as a jolt we experience by touching a doorknob after walking across a rug in dry weather, or as dire as the crash of the *Hindenburg*, where one theory for the cause of the airship fire is that a static spark ignited a hydrogen leak. Such discharges are a major concern for NASA because the dry conditions on the Moon and Mars are ideal for triboelectric charging: An astronaut, reaching out to open an airlock after a walk on the dry surface, may cause a discharge that could zap critical electronic equipment. But not all static is a nuisance: Triboelectric charging, when controlled, is at work in products such as copiers and laser printers.

Although static electricity is a familiar subject, much still remains unknown

about how and why such charges form. Research across many disciplines of science and engineering, from physics and chemistry to medicine and meteorology, is currently being conducted on triboelectricity’s various aspects. However, relatively few scientists are engaged in understanding it at a fundamental level.

Contact charge exchange between two metals is known to result from the transfer of electrons. But when at least one of the materials is an electrical insulator, there is no general understanding of what carries charges from one surface to the other. Different theories have proposed either electrons or ions. An electron is a subatomic particle carrying a negative electrical charge; an electrical current involves movement of electrons in a metal conductor. An ion, on the other hand, can carry either a positive or a negative electric charge; they are known as *cations* and *anions*, respectively. A cation has fewer electrons than protons, giving it a positive charge. An anion possesses more electrons than protons, so it has a net negative charge. Cations and anions can be atoms, molecules or polymer fragments. Evidence has been discovered for both electron and ion transfer under specific experimental conditions, but these data are limited and frequently contradictory. Recently, new research has demonstrated that charge exchange can also result from the physical transfer of tiny amounts of surface material from one substance to another. An understanding of how this occurs on a molecular level is now just beginning to emerge. It is becoming increasingly clear that more than one mechanism can occur simultaneously, and what happens may depend on the material compositions and conditions of the experiments in ways not yet known.

Remarkably, why charge exchange happens at all when insulators are involved is even less well understood than how it occurs, although the inherent complexity of the problem has long been

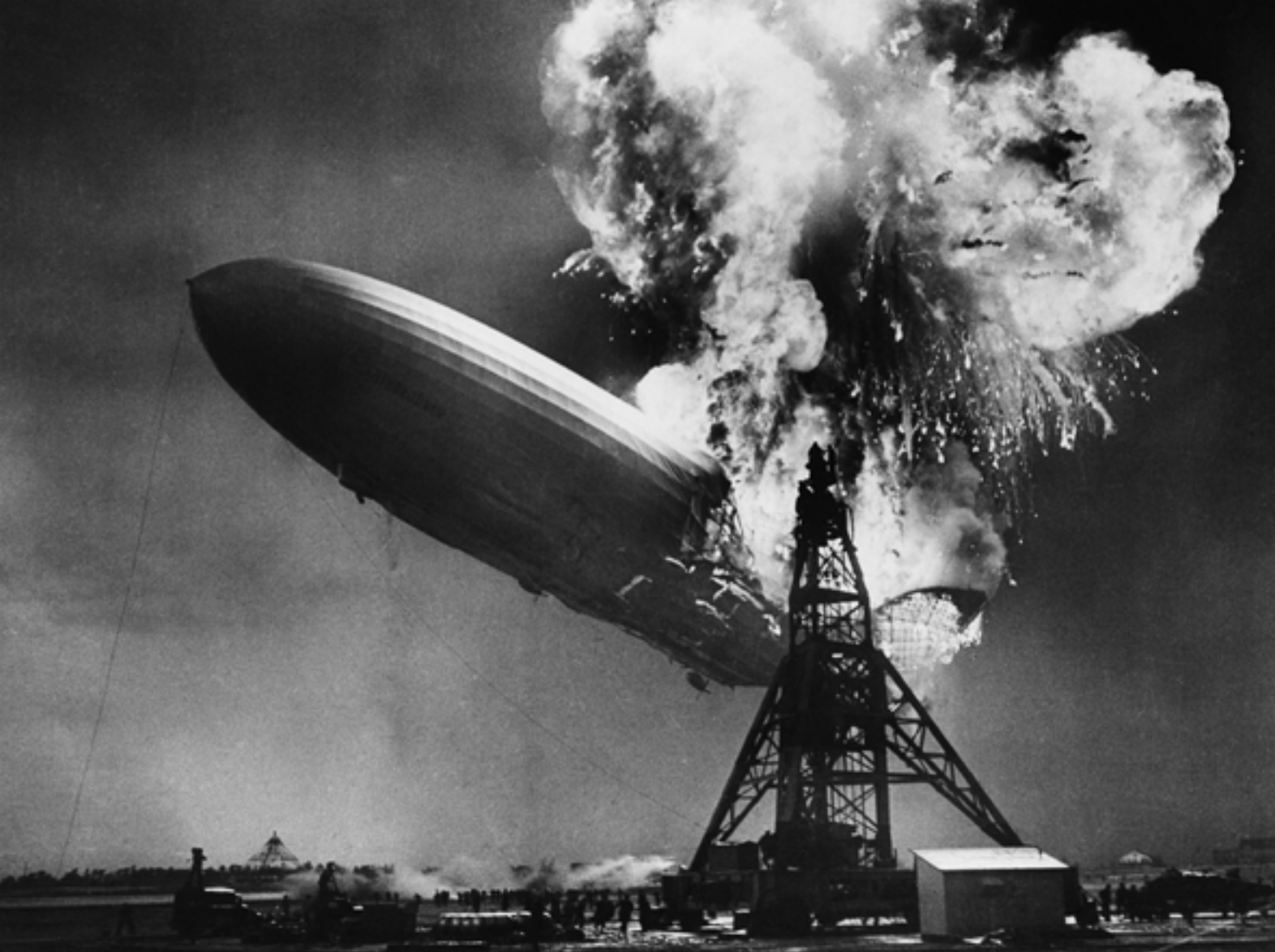
appreciated. How does a material that by definition does not conduct electricity nonetheless gain an electrical charge? Three questions must be answered: Are the charge exchange species electrons or ions, what is the driving force for charge exchange and what limits the charge exchange? Traditionally considered to be a problem in physics, progress on finding the specific mechanisms of charge exchange did not really begin until the application of several areas of chemistry.

One reason that answers have been slow in coming is lack of incentive: Most research involving triboelectricity is applied to the development of new technologies and to solving problems, and understanding the mechanisms of charge exchange is not required for these purposes—a charge is just a charge, regardless of how and why it occurs. However, a clear picture of charging mechanisms could contribute to useful purposes when it becomes available.

The Experience of Xerox

By far the most important commercial products based on triboelectricity are copiers and laser printers (which use the same technology as copiers but incorporate a laser input), both pioneered by Xerox Corporation. Electrophotographic copiers are based on two phenomena: triboelectric charging and photoconductivity. *Photoconductors* are materials that become better conductors of electricity when exposed to light. Exposure of a charged photoconductor to a light image of a document results in discharge of the illuminated area. Charged toner particles are allowed to be attracted to the image pattern on the photoconductor, transferred to paper and fused to produce a copy. The toner is triboelectrically charged by mixing it with a carrier, forming what’s called a developer. Carriers typically consist of beads 100 micrometers in diameter, which are partially coated with a poly-

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Bettmann/Corbis

Figure 1. A static, or triboelectric, discharge may have caused the airship *Hindenburg* to explode into a huge ball of fire as it came in for a landing. Static isn't all bad: It makes copiers and laser printers possible. But what actually creates triboelectric charges remains a cutting-edge field of research.

mer. Toner and carrier compositions are selected for optimum triboelectric charging, among other requirements.

It was reasonable at one time to believe that a basic understanding of triboelectricity could provide input into the design of developer materials. The early success of copiers did provide such an incentive, but this achievement continued in spite of no progress in deciphering the mechanisms of triboelectric charge exchange in terms of electron or ion transfer.

It was at Xerox in the 1970s that I first developed an interest in this subject when employed as a research chemist with the objective of applying chemistry to the basic understanding of how triboelectric charging is related to material compositions. The first Xerox copiers, introduced in 1960, had barely acceptable copy quality, which resulted from totally empirical efforts at the Battelle Memorial Institute to design developer materi-

als without any basic understanding of triboelectricity. The difficulty of achieving acceptable copy quality increased exponentially with process speed, with the consequence that introduction of the high-speed 9200 copier in the 1970s was not an immediate success—a clear indication that the Xerox version of electrophotography (which they referred to as xerography) was approaching its limits.

Around that time, Xerox gained access to a new kind of electrophotographic technology that provided dramatically superior copy quality. It involved conductive developers and toner charge control using additives, a concept later used to provide the first evidence for an ion transfer mechanism in contact charge exchange. This result came from a fortuitous series of events starting with competitive analysis—an episode that now appears to be a missing part of Xerox history. In 1973, a team of five physi-

cists and one chemist (myself) was asked to analyze the large number of copier-related patents that had been issued to Kodak. Each of us was assigned to a different copier subsystem, with the objective of determining whether Kodak had serious intentions of entering the copier field. I was assigned to review developer materials, and I was the only member of the team to conclude that Kodak did plan to introduce a copier. Consensus prevailed, with the consequence that, when the first Kodak Ektaprint copier was introduced in 1975, Xerox was caught by surprise on several fronts.

An Ektaprint copy appeared on my desk with the request that I explain to Xerox management how Kodak could produce copies of vastly superior quality compared with the best Xerox copies at that time—in terms of coverage of the solid areas, edge acuity of the printed letters and low levels of stray

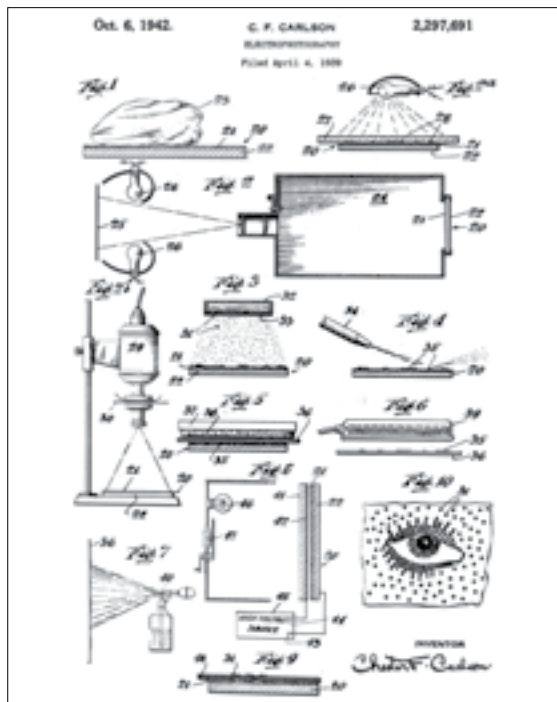


Figure 2. Chester Carlson spent many years (and endured much trial and tribulation) inventing the first xerographic apparatus (left). His patent describing the process, called *electrophotography*, was issued in 1942 (right). (Images courtesy of Xerox Corporation.)

print on the background. My presentation was received with a high level of disbelief because the Kodak technology differed so much from the basic design assumptions held by Xerox. It quickly became evident from analysis of the Kodak developer that their image quality resulted from the use of a *conductive developer* (with positively charged toners) as opposed to the *insulating developers* (with negative toners) in use by Xerox.

The positive toners resulted from Kodak's empirical discovery of charge control agents that generate and control pos-

itive charges by incorporation of *quaternary ammonium salts* (consisting of a cation with a central nitrogen atom attached to four hydrocarbon groups, paired with an anion such as a chloride ion). Clearly Kodak had shown the scientific prowess of their chemists relative to those at Xerox! The skills needed to design electrophotographic developer materials are the same as those needed to begin the process of understanding triboelectric charging of polymers—skills based on chemistry, a major strength at Kodak but a relative weakness at Xerox. Yet in spite of this Kodak advantage, the field was

later more than evened by Xerox through an unusual set of circumstances.

The difference in copy quality was of such magnitude that Xerox immediately realized the need to use the Kodak technology. Xerox physicists fervently studied how superior image quality resulted from the use of conductive developers. A team of chemists was established to produce and test toners containing a large number of different quaternary ammonium salts in conductive developers. This activity resulted in a series of at least a dozen patents based directly on the Kodak design, filed between 1978 and 1985 and issued to Xerox between 1980 and 1987; I was co-inventor of several of these advances. Remarkably, Kodak never challenged these patents. Kodak's tightly patented technology for producing copy quality superior to that of Xerox and IBM gave it the potential to dominate the copier market, but it failed to capitalize on that advantage and later withdrew from manufacturing copiers. Under what circumstances did Kodak give away their copier-technology crown jewel, especially to a

Figure 3. U.S. Patent 3,893,935 was issued to Kodak in 1975, claiming use of quaternary ammonium salts as charge control agents in copier toners. An example of one such salt molecule is tetrapentylammonium chloride, which has a mobile chloride ion (green) that is the agent of charge exchange.

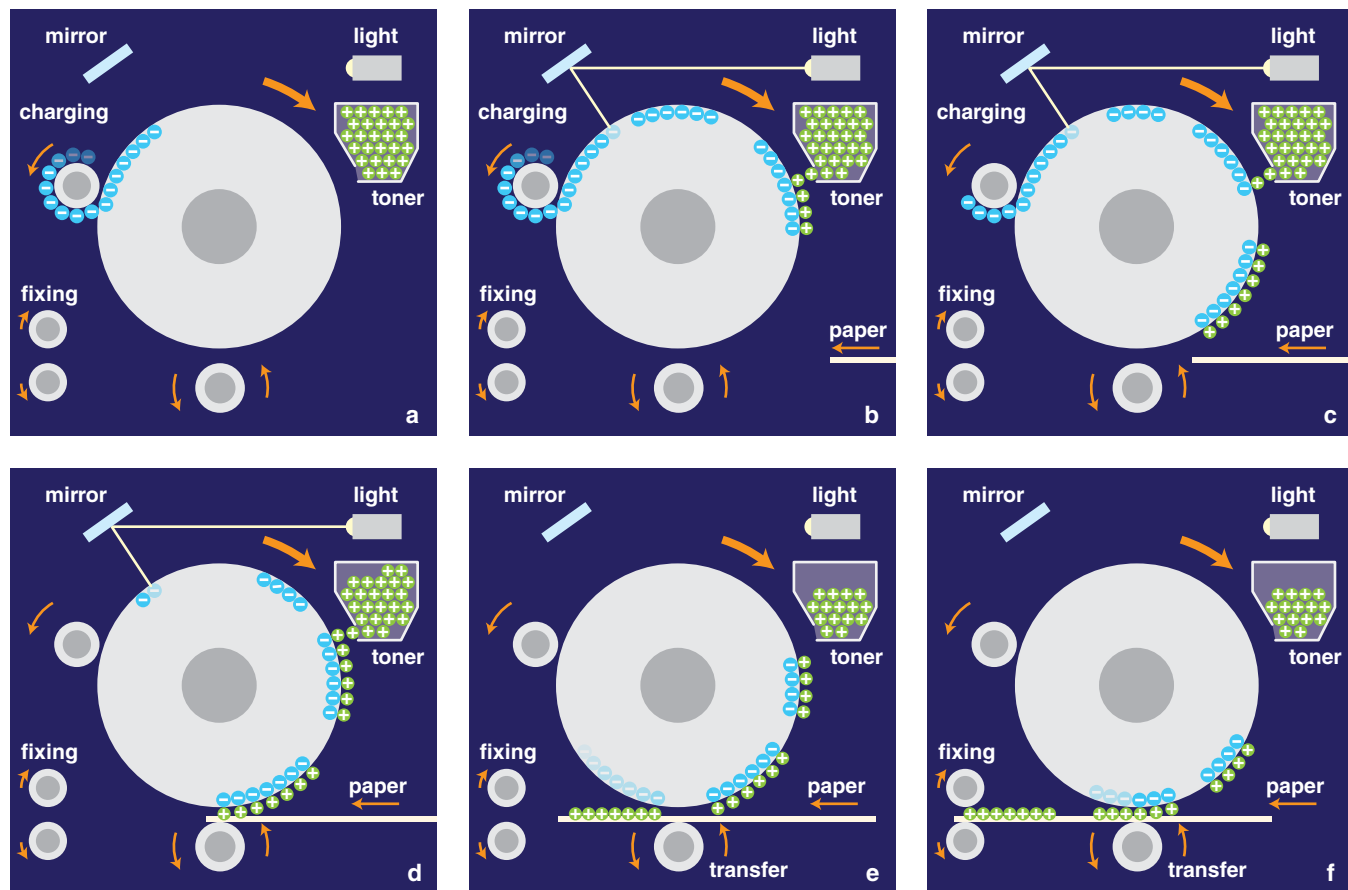


Figure 4. A copier makes use of static electricity, as shown in this sideview schematic. A photoconductive drum or belt is negatively charged (a), and a light discharges those areas that will not be part of the printed image (b). Positively charged toner is attracted to the negatively charged surface of the drum (c), and then transferred onto paper (d and e). Heat fixes the toner permanently onto the paper to create the final printout (f).

well-established competitor—a subject of some interest in light of the current state of Kodak's fortunes? Could it be related to a Federal Trade Commission (FTC) complaint issued against Xerox in 1973 for alleged unfair competitive practices? Xerox chose to settle the case instead of undertaking litigation. As part of the settlement, Xerox was required to license all patents relating to copiers to competitors, but in return "Xerox may require the cross license of any patents of any licensee...." Why did Xerox accept such an onerous settlement in a case whose legal issues were relatively evenly balanced, according to statements by Frederic M. Scherer, then FTC chief economist? Was it mainly to gain access to Kodak's U.S. Patent 3,893,935 claiming the superior developer materials, which threatened Xerox's future?

Xerox electrophotographic imaging technology had hit a ceiling in the 1970s for which their research laboratories had no solution, and it was rescued from this potentially disastrous business problem by adopting Kodak technology, conductive developer materials with positively

charged toner. I played a central role in the Kodak analyses and still have the original documentation, but surprisingly these developments are not included in any historical accounts of Xerox copier technology. Indeed, one of the authors of one Xerox history had personally studied conductive developers and published his results elsewhere in 1987. Competitive analysis is standard business practice, so one wonders at such selectivity in historical documentation.

A Xerox physicist and prominent early inventor made a comment on Kodak patent strategies at the 2003 Lemelson-MIT Program Intellectual Property Workshop on the subject: How Does Intellectual Property Support the Creative Process of Invention? He stated: "Kodak was using trade secrets more often [than patents] ... They would rather keep their inventions as trade secrets, because they did not want them to expire." A curious comment indeed, considering the major contribution that Kodak patents made to Xerox technology, and especially because this remark was made in the presence of the workshop chair-

man, a retired Xerox senior executive who had been a physics manager at the corporation in the 1970s.

As a consequence of the Kodak-Xerox events, Xerox had found a solution to their imaging problems—and motivation for basic research in triboelectricity at Xerox was lost.

Evidence for Different Mechanisms

Triboelectricity was classified as a problem in solid-state physics because contact charging between two metals had been well understood in terms of the physics of electron transfer. The driving force for this transfer is the difference between the metals' *work functions*, the energy required to remove an electron from a metal surface. For metal-polymer contacts, researchers had found linear relationships between the density of charge created on a polymer and metal work functions, which was presented as evidence for an electron transfer mechanism. It was later reported that this relationship is not always present, but this discrepancy was attributed to the difficulty of obtaining reproducible results due to the many

variables involved and the possibility of more than one simultaneous mechanism.

For charging between two insulators, physicists developed theories based on the assumption of an electron transfer mechanism. Although not contributing to the question of the nature of the charge exchange species, these theories have had debatable success in addressing the driving force for charge exchange in terms of the “effective work functions” of insulators. This concept is

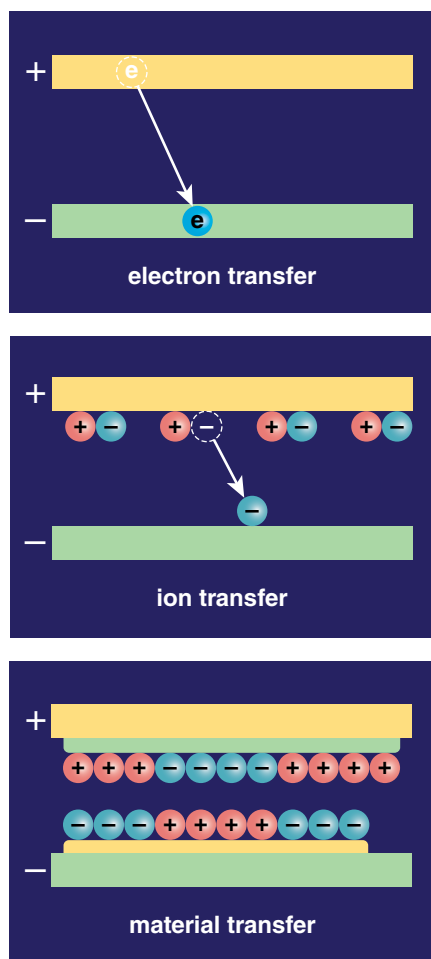


Figure 5. Current research shows that triboelectric charges happen by three different mechanisms, some or all of which make take place simultaneously. The first established mechanism is electron transfer (top), where an electron from a metal tunnels into the bulk of a polymer after they come into contact and are separated. Evidence also exists for ion transfer (center), where contact causes one member of a pair of positive and negative ions to relocate to the other surface, which can be a polymer or a metal. New data now point to material transfer as a mechanism of charge exchange between two polymers (bottom). A physical clump of material rubs onto each opposing surface, and this material has a mosaic pattern of domains of positive and negative polymer-fragment ions that sum to an overall difference in charge between the two surfaces.

of questionable validity because there are no available free electrons in insulators. But such theories have been more successful in accounting for the limit of charge exchange in terms of the electric field generated by the charges in some cases. In other circumstances, charge buildup is limited when the ambient electric field becomes large enough to exceed the *dielectric strength* of the surrounding air, pulling apart the electrons from the air molecules and turning it from an insulator to a conductor, thus leaking current away from the material.

Clearly, a physics approach was insufficient to address the multidisciplinary problem, but the predominantly physics culture at Xerox didn't recognize that limitation. Eventually a concession was made by a Xerox chemist who reviewed models for the electronic structure of organic polymers, with a focus on those having highly ordered groups with rigid, periodic arrays of atoms, some having nearly metallic properties. He concluded that “the description of the electronic structures of these materials requires the introduction of concepts more familiar in the fields of electrochemistry and physical chemistry than solid-state physics.”

It was two decades after the Kodak discovery of toner charge control agents that researchers used this design approach, an example of the chemistry concept of *mobile ions*, to produce evidence for an ion transfer mechanism for triboelectric charging. Many researchers contributed to this major advance, including Arthur Diaz of IBM Almaden Research Center in San Jose, Howard Mizes and Kock-Yee Law of Xerox Corporation, and Logan McCarty and George Whitesides of Harvard University. A mobile ion has freedom to transfer from one surface to another, because it has a *counterion* of opposite charge that is either significantly larger and has less mobility, or is attached to a polymer and has no freedom to transfer. With molecules and polymers containing a mobile ion, the mechanism of charge exchange has indeed been related to the transfer of this ion, both to the sign of charging and to its magnitude. But the driving force for this mechanism remains elusive. Charge exchange of equal magnitude also can happen when polymers do not contain mobile ions, so an additional mechanism must be at work. In 2008, McCarty and Whitesides found an answer with their hydroxide ion hypothesis, in which water molecules within the thin water layer between polymers dissociate, with

preferential adsorption of the resulting hydroxide (OH⁻) ions to one surface. Electrokinetic evidence supported their hypothesis. But experiments in 2011 by Bartosz Grzybowski and his group at Northwestern University, designed to verify this hypothesis, have shown that charge exchange can take place between two nonionic polymers in the total absence of water, thus implicating a mechanism entirely different from both the proposed hydroxide ion hypothesis and ion transfer in general. However, their result does not preclude the hydroxide ion mechanism in the presence of water, perhaps representing another situation in which more than one mechanism can apply simultaneously.

Major advances in understanding the methods of charge transfer have been reported in the past few years, and in all of them charging results from the application of a significant amount of mechanical force between two polymers, specifically in pressing, rubbing and shearing contacts. The field is currently being revolutionized by the application of surface analysis—electrical, chemical and electrochemical. It has long been known that contact of a polymer with another material can result in the transfer of some of the polymer from one surface to another; it was also established that, on a macroscopic scale, a triboelectrically charged surface may have both positive and negative regions. In 2011, using *Kelvin force microscopy*—a high-resolution analysis of a surface's electrical properties—Grzybowski and his team demonstrated that material transfer can be accompanied by charge exchange on a nanoscopic level when two polymers are pressed together for varying times and degrees of pressure and then separated. This kind of charge exchange was unexpected. For centuries, it had been assumed that, in such contact charging, one surface charges to become uniformly positive and the other uniformly negative. The group found that, although each surface develops a net charge of either positive or negative polarity, each surface also supports a random mosaic of oppositely charged regions in nanoscopic dimensions. The net charge on each surface is the arithmetic sum of the positively and negatively charged domains. This finding means that more charges are being exchanged than previously assumed. Charging is not an event affecting one in 10,000 surface groups, but more of the order of one charge in 100 surface groups.

Various types of spectroscopy and chemical analysis of the surfaces revealed oxidized species, believed to be responsible for the charging. This material transfer mechanism was a landmark advance in that it represented the first departure from the electron/ion transfer mechanisms, and also for the first time it accounts for the driving force for charge exchange. Pressing two polymers together, followed by separation, causes small clumps of materials to transfer between the surfaces. For this exchange to happen, covalent bonds must be broken, with the formation of polymer fragment *free radicals* at both scission sites. Free radicals are atoms or molecules having unpaired electrons, which cause them to be highly chemically reactive, and it is believed that they react with ambient oxygen and water to form the charged species.

In 2012, Fernando Galembeck and his coworkers at the University of Campinas in Brazil took this material transfer mechanism a step further. Teflon and polyethylene were sheared together—pressed and twisted against one another. After separation, the team found macroscopic domains or patterns, both positively and negatively charged, analogous to those reported by Grzybowski's group. Materials extracted from the surfaces with solvents were identified as polymer ions. The Teflon residues were predominantly negatively charged, and the polyethylene residues were primarily positively charged. Galembeck's team proposed this mechanism: High temperature at the frictional points of contact results in polymer plasticization and/or melting. Shear forces cause breaks in the polymer molecules' chains, forming polymer-fragment free radicals. Electron transfer from the polyethylene radicals to the more electronegative Teflon radicals converts these free radicals to positive and negative polymer ions, respectively, which are known as *amphiphiles*. Charged macroscopic domains form due to a combination of two factors: Amphiphiles at interfaces are known to sort themselves into arrays when they are in the type of polar environment created by the ions, and Teflon and polyethylene are immiscible.

A comparison of the work of Galembeck and Grzybowski illustrates the complex interaction between polymer properties and the nature of the contact in affecting the charge exchange mechanism. The contribution of each of the factors Galembeck identified in the material transfer mechanism depends on the viscoelastic, topographical, chemi-

cal and other properties of the specific polymers used, and also on the nature of the contact. For example, the ease of bond scission would differ between polydimethylsiloxane (PDMS), a polymer having a silicon-oxygen backbone, employed by Grzybowski, and the carbon backbone-based polymers used by Galembeck. The degree of melting, or plasticization, can be expected to be less in light, low-friction contacts than in shear or vigorous rubbing contacts, on account of the lower temperatures involved, in addition to being affected by inherent polymer properties such as glass transition temperature (where the material changes its flow properties without any change in molecular structure). But polymer-chain scission of a soft polymer such as PDMS can occur at lower temperatures in low-pressure,

low-friction contacts on account of the polymer chains entangling at the interface, which break on separation. Such entanglements are enhanced in silicon-oxygen backbone polymers by the presence of oligomers (fragments of polymers) and cyclic oligomers (where the fragments have a ring structure). These substances exist in *dynamic equilibrium*; they are modified constantly due to the continual opening and closing of silicon-oxygen bonds, but have no net change. In the material transfer mechanism the driving force for creation of the charges is the input of mechanical energy during the contact of the polymers.

Research advances have also been made recently for rubbing contacts between two polymers. In 2008, Chongyang Liu and Allen Bard at the University of Texas at Austin, and indepen-

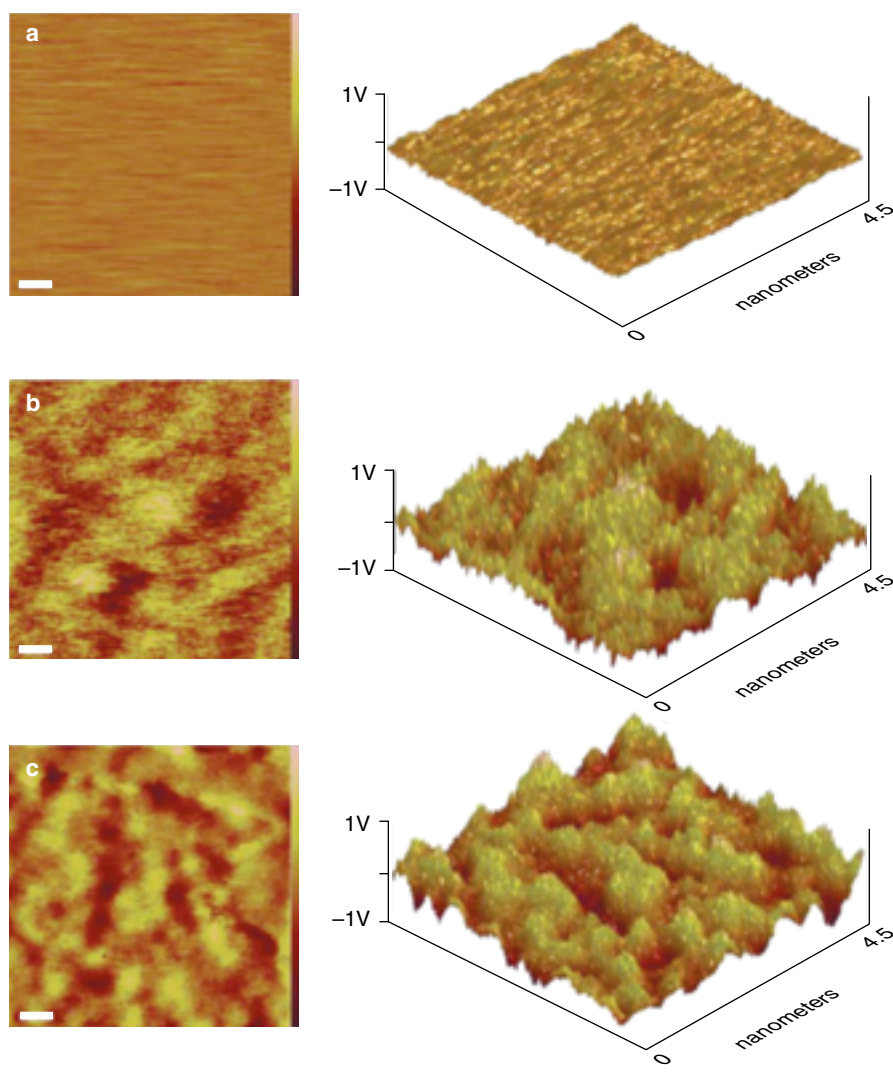


Figure 6. A technique called Kelvin force microscopy shows the transfer of nanoscopic clumps of polymers between surfaces after contact and separation. Before contact (a), the material is relatively smooth. Contact with a polymer of the same composition (b) and of a different makeup (c) yields different transfer patterns. (From H. T. Baytekin et al., *Science* 333:308, reprinted with permission of the American Association for the Advancement of Science.)

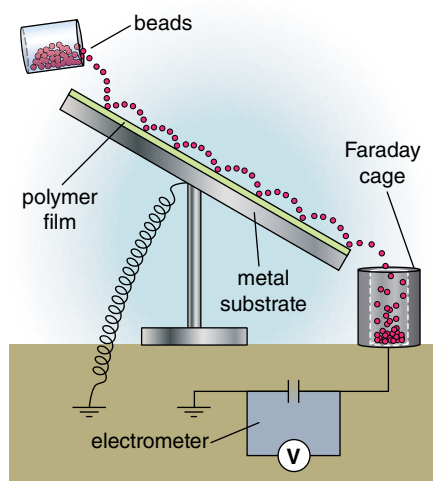


Figure 7. In order to study how polymer composition at different depths affects charging, the author used metal and coated beads bouncing down a polymer-layered metal plate. The results can now be seen as supporting material transfer, as metal beads gouge a deeper layer and affect the inner layers of the polymer film.

dently Toribio Otero at the Polytechnic University of Cartagena in Spain, proposed an electron transfer mechanism on the basis that, after separation, the surfaces were able to induce several electrochemical reactions that can only be caused by electrons. Their interpretation was challenged in 2011 by Silvia Piperno and her colleagues at the Weizmann Institute of Science in Israel, who proposed an ion transfer mechanism based on the transfer of material containing polar species. Also in rubbing contacts between two polymers, bipolar charging patterns were reported in 2011 by Nikolaus Knorr of the Sony Materials Science Laboratory in Stuttgart, Germany.

A Complex Relationship

Triboelectric charging results from contact between surfaces, but precisely what is meant by each of these terms is not defined or understood as they relate to charging. My interest has focused on these questions: How are triboelectric charging mechanisms related to the depth of a polymer surface (the *charge penetration depth*), and how does this depth vary as a function of the nature of the contacts? Many different types of contact have been employed in innovative experimental designs, but apparently no efforts have been made to study this factor as a controlled primary variable. In the many studies of triboelectric charging of polymers, no account was taken of the fact that polymers are typically not

compositionally or morphologically homogeneous as a function of depth.

It is well known that low-surface-energy additives in polymers will migrate to the surface if films are fabricated from solution so as to allow thermodynamic equilibration of the components. I used this phenomenon while at Xerox in the mid-1970s to investigate charge penetration depth. A series of polymers was prepared whose topmost compositions, determined by X-ray photoelectron spectroscopy, were designed to be different from the known bulk compositions. Triboelectric charging was determined by cascading small (100 and 250 micrometer) beads, both bare metal and polymer coated, over inclined polymer films cast on aluminum plates, a method of established precision and reproducibility. The bouncing contacts were light and brief, having a calculated contact time of 0.00001 second. The surprising finding was that contact charging between two polymers relates to their topmost molecular layers, but between a metal and a polymer it relates to layers beneath the polymer surface. The hypothesis was that the former results from ion transfer between the topmost surfaces and the latter involves electrons tunneling into the bulk, thus postulating a relationship between charging mechanism and charge penetration depth, which is supported by the fact that ions are known to adsorb to polymer surfaces and electrons are considered to burrow into them.

In view of the new evidence for a material transfer mechanism, I have subsequently reported that the above results can equally well be interpreted by material transfer: Contact of a polymer film with a rough, hard metal surface, on account of its greater applied force, gouges out a deeper layer than contact with a smoother, softer polymer surface. It follows that electron, ion and material transfer mechanisms can possibly occur simultaneously, depending on the materials and conditions of contact. For metal-insulator contacts, the electron transfer mechanism has been sufficiently established under some circumstances. For contact between two insulators, the issue is whether material transfer is the only or the predominant mechanism in all contacts.

Alternative concepts include a threshold of applied force or energy below which insufficient material is transferred to cause charge exchange, or a continuum of contact types in which electron, ion and material transfer all take place,

with elevating involvement of the latter with rising force or applied pressure. Quantitative evidence by Law and his colleagues in 1995 for ion transfer is of interest in this context. Toner coated with a cesium salt was gently tumbled with polymer-coated carriers. Linear correlations were found between charge exchange and the degree of cesium transfer as a function of mixing time, providing strong evidence for a cesium-ion transfer mechanism. Mobile ions, by their very nature, would transfer more easily than fragments of a polymer, which would require bond cleavage. Could this mean that the mechanical forces between toner and carrier were too low for simultaneous transfer of polymer fragments? Is there a hierarchy of charge exchange mechanisms, so that several mechanisms can contribute to charging in accordance with their position in the ranking, until a limiting charge is attained? In support of this theory, Law's group found the same correlations between charging and ion transfer with bare metal carriers, indicating that transfer of mobile ions, when present, takes place in preference to electron transfer, which has been demonstrated in different experiments by correlations with metal work functions.

Identical Materials

A phenomenon that continues to puzzle experimenters is that contact charging occurs between materials of identical



Figure 8. A Van de Graaf generator creates a static charge that causes a patron's hair to stand on end. The everyday occurrence of static may soon be better understood due to new research.

compositions. As stated in a 2011 review paper by Daniel J. Lacks and R. Mohan Sankaran of Case Western Reserve University, "Another open question is the contact electrification that occurs when two insulating materials with identical physical properties touch—since there is no apparent driving force, it is not clear why charge transfer occurs." The charging of identical materials is in contradiction to the long-standing and oversimplified concept of the *triboelectric series*, where materials have been ranked according to their propensity to charge positively or negatively. A material charges positively relative to all the materials below it in the series, which implies that a difference of composition is necessary for contact charging. Yet charging occurs when identical polymers are either pressed or rubbed together, symmetrically or asymmetrically. Asymmetric rubbing of polymer films results when a small area of one polymer is contacted with a larger area of the other. The direction of charging is dependent on the materials involved.

As is frequently the case, it is such unexpected phenomena that are likely to provide critical mechanistic information. I have proposed a mechanism for charge exchange between identical materials as an extension of the concept that the depth from which material is transferred from a polymer surface increases with applied force. Asymmetric rubbing results in unequal forces applied to each surface, so that material from different depths would be transferred. Because polymers are typically inhomogeneous in their vertical compositions, this asymmetry would cause the transfer of material of different compositions, resulting in net charges of different signs in the bipolarly charged separated surfaces.

Alternatively, differences in the degree and type of mechanical force applied to each surface could result in subtle differences in the *mechanochemistry*, chemical reactions resulting from the application of mechanical force. Sufficiently different compositions of polymer fragment ions could be created at the two surfaces where charge exchange occurs.

This new mechanism could also apply to symmetrical rubbing and pressing of identical polymers on the basis that small, unintentional degrees of asymmetry could result in sufficient asymmetric compositional transfer to result in charging. It would apply equally well to charging between materials of different compositions and, in this way, contrib-

utes to the understanding of the general material transfer mechanism. Differences in hardness or softness could also contribute to asymmetric material transfer. The use of polymers designed to have compositional inhomogeneity as a function of depth, such as those described in experiments earlier, would provide a sensitive test for this hypothesis because the transfer of materials with different compositions would be easily detected.

Triboelectric charging of compositionally identical materials also happens with particulate matter, as in dust storms and the industrial handling of fine particles. Again, such occurrences could come from asymmetric contacts that result from differences in particle size. The larger particles charge positively and the smaller particles negatively. An electron transfer mechanism has been proposed in which electrons trapped in high-energy surface states transfer to lower-energy states in other particles during collision. Previous research has been done with the assumption that surface compositions and other surface characteristics do not vary as a function of particle size, which could be incorrect.

Completing the Picture

There is an increasing need to create materials that do not charge upon contact, perhaps most importantly because of the continued miniaturization of electronic equipment, which renders it even more susceptible to damage by even low-voltage discharge. Another motivation is pure research, whose objective is the understanding of natural phenomena and observable facts with no specific application or problem solving in mind. For contact between two polymers, studies of the interaction between variables relating to polymer composition and contact type should throw light on key questions such as: For contacts involving polymers containing mobile ions, what are the factors affecting the contribution of ion versus material transfer? And when a metal is involved, what are the factors affecting the contribution of electron versus material transfer?

In addition, recent developments have brought attention to the need for the application of mechanochemistry, which is central to the material transfer mechanism. Integrating the separate pieces of the puzzle into a coherent overall picture will take multidisciplinary efforts. Complex problems increasingly require input from several scientific disciplines. Studies have shown that the

average size of teams required to produce peer-reviewed publications over the past 50 years has increased by 20 percent each decade. It is likely that this once physics-only field will continue to grow and find answers in many other realms of the sciences.

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