The trick of rubbing a balloon on your head to make hair stand up has generated giggles for ages. But the electrical phenomenon behind the trick can also generate energy. In the past decade, scientists have harnessed it to make devices that could produce enough power for sensors, electronic devices, and—if deployed on a large scale—maybe even homes.

The phenomenon, called the triboelectric effect, is the buildup of charge on dissimilar surfaces after they touch each other. Separating the surfaces creates a large voltage that can trigger a flow of electrons—hence those static shocks when you touch a doorknob while wearing a wool sweater; charge builds up from skin rubbing against the wool and is released when metal is touched. Although triboelectricity has been known for centuries, only recently have researchers been able to create materials and design devices to capture the current to produce useful amounts of power.

Triboelectric generators can convert motion into electrical signals inexpensively using everyday materials like nylon and wool. Because those electrical signals can also be used to sense motion, developers imagine self-powered touch sensors and heart rate or respiration sensors that power themselves by harvesting energy from beating hearts and expanding lungs. Or shoes and fabrics that turn walking and breathing into power for wearable electronic devices and smartphones. Or large triboelectric devices that could usher in a new era of harvesting power from the motion of rolling waves, flapping sails, or windows pelted with raindrops.

Materials scientist Zhong Lin Wang of the Georgia Institute of Technology pioneered triboelectric nanogenerators (TENGs), reporting the first device in 2012. The group’s powerhouse work has inspired many researchers: Around 5,000 scientists worldwide now work in the field, and hundreds of papers flood journals every year, Wang says.

Triboelectric nanogenerators have seen faster progress than any other form of energy harvesting, says Peter Harrop, chairman and founder of the market research firm IDTechEx. Improved circuit and system designs have boosted performance, and researchers have demonstrated proof-of-principle devices for applications ranging from milliwatt-scale patches to conceptual megawatt-generating blankets floating on the sea.

Yet, there are no TENG-powered gadgets for sale, let alone large-scale triboelectric energy harvesters. The technology is simply not reliable and predictable enough, Harrop says. “With TENGs, you can do lot of party tricks, but reproducibility is a serious problem.” It is difficult to make several...
devices that work in an identical fashion, and even the same device can behave unpredictably over time, he says.

More materials research of the kind that Wang and others are doggedly pursuing should help, as would better understanding of the fundamental mechanism behind the triboelectric phenomenon. But the key for commercial success might be to nail the right uses for the technology, says Ramakrishna Podila, a physicist at Clemson University. “It’s not going to change the world, but there are a lot of cool applications.”

Charging up

Back in 2011, Wang’s students stumbled upon TENGs when studying piezoelectric materials, which are ceramics that can convert mechanical force into electricity and back. They found that flexing a thin film of polyethylene terephthalate (PET) placed next to a sheet of metal produced current that could charge batteries and power LEDs. The nascent TENGs could convert up to 15% of the mechanical energy into electricity, with a fingernail-sized device producing a few milliwatts—enough for a pacemaker. A larger 5 cm by 5 cm patch could charge a lithium-ion battery for a cellphone.

Not only were triboelectric devices more powerful than their piezoelectric cousins, the team realized, the choice of materials was huge, and devices were easy to make. “You can use any material you can think of,” Wang says, as long as it can be fabricated at scale. “I wonder why this was a forgotten corner in the field of physics.”

Typical TENGs combine electron-donating materials, such as aluminum, copper, and nylon, with electron-capturing dielectric polymers, such as polytetrafluoroethylene (PTFE), polydimethylsiloxane (PDMS), and polyimide (PI). Pairing the right materials is important, Wang says. So is the microstructure of materials. Increasing the surface area where the materials meet by adding microstructures to create just enough roughness—not too little, not too much, Wang says—increases the charge density and thus the power output. Altering surfaces by chemically adding functional groups can also improve charge density.

Wang and his group have built countless TENG devices. Covering stainless steel fibers with PET, cotton, and wool, they make yarn that can be woven into energy-harvesting, washable patches that generate tens of milliwatts per square meter. They have woven strips of nickel-coated PET and PI-coated copper to make flags that can power temperature and humidity sensors when fluttering in the wind. And they’ve put TENGs made of PDMS and PET in shoe insoles that use footsteps to power a global positioning system device.

Performance has “gigantically improved” over the years, he says. His lab’s devices can now convert mechanical energy to electrical energy with efficiencies of over 50% and can work for three years. The power density can be as high as a few hundred watts per square meter, meaning a 10 cm × 10 cm device could, very slowly, recharge an iPhone battery.
endless combinations of materials and device designs, researchers have demonstrated self-powered temperature and pressure sensors; biodegradable and implantable TENGs; devices that monitor breathing and pulse; and microphones powered by sound vibrations.

Are we there yet?
The astonishing number of devices that have been developed in the lab has raised tantalizing prospects of commercial devices. But TENGs won’t become practical until researchers can develop higher-power devices that can endure real-world conditions and last for years. Probably the biggest missing piece is a deeper understanding of the fundamental quantum nature of the mechanism behind triboelectricity. That would mean less guesswork to create more predictable, high-performance, reliable devices.

In addition, some researchers call for designing and creating new, better triboelectric materials, especially electron-donating materials or more durable composite materials. But Clemson’s Podila disagrees. “My view is don’t invent a new material when you don’t need it,” he says. Out-of-the-box thinking with existing materials could suffice instead. Most work has centered on tweaking surface roughness of common organic polymers to boost charge density. There might be other paths, such as changing adhesion energy between the surfaces, finding new ways to chemically modify surfaces, or altering intrinsic properties such as dielectric constant.

Another simple way to boost power output is to increase the polymers’ conductivity. Nonconductive polymers produce dismal electric currents despite the large voltage spikes created by charge separation. Podila and his colleagues deposit conductive indium tin oxide on their PET–PI TENGs, which increases the current. He also proposes abandoning costly, complex manufacturing methods in order to produce TENGs on a large scale. Instead of etching patterns on surfaces using lithographic techniques, he 3D prints a microstructured film out of a graphene–polyactic acid composite and couples it with a Teflon film to make a TENG.

IDTechEX’s Harrop points to the need for better standards and transparency. Research papers on TENGs tend to lack detailed data, which makes reproducibility difficult, he says. And while agencies like NREL typically test and certify other energy technologies, as of yet “there’s no referee for TENGs; it’s the Wild West out there,” he says.

These limitations, however, do not negate the “wonderful advantages” of triboelectric generators, he says. The devices use cheap, nontoxic, and readily available materials that can be woven and layered, and made stretchable, conforming to the way technology is going in general with wearables. “There are people screaming for good energy harvesting,” Harrop says. Companies should be working with the researchers and developing new uses. The technology needs some imaginative marketing.”

Finding the right fit
Nevertheless, it’s important to keep expectations real, says Trisha L. Andrew, a chemist at the University of Massachusetts Amherst who studies textile electronics. The energy-harvesting field is rife with contenders, including well-established solar technologies and newer ones like piezoelectrics and thermoelectrics.

“Triboelectrics are pretty terrible at energy generation,” Andrew says. Laboratory TENG devices give a few milliwatts per square centimeter, and scaling them up would yield just a few watts per square meter. So realistically, an entire shirt would only produce hundreds of microwatts, she points out. The idea of using triboelectrics to reliably power gadgets like smartphones in real-world settings seems far-fetched to her. Instead, she is focusing on using the technology to make sensors that can detect body motions like footsteps, heartbeats, or joint movement. She makes triboelectric

Researchers have proposed embedding triboelectric nanogenerators in shoes (bottom) and in backpacks (top) to harvest energy from human movement. Credit: ACS Nano 2021, DOI: 10.1021/acsnano.0c07498; Zhong Lin Wang laboratory.
fabrics by combining fibers like polyurethane and elastane with wool or cotton, or by coating off-the-shelf textiles with conductive polymers. Through her new startup company, she plans to create products for sleep sensing and for touch-sensing toys.

Podila is working with the Clemson University Research Foundation to embed his TENG devices, which produce about 70 mW from a few newtons of force from footsteps, into light-up tiles for interactive videogames and airport walkways. He is also excited about a novel defense-related application he is developing through his startup SAI Global Technologies. The patent-pending idea is to strike a TENG device with a high-velocity object and use the resulting large voltage spike to generate a burst of electromagnetic energy to knock out enemy electronics. Another area in which TENGs could excel, he says, “should be space applications, like rovers, which are in places where there is no sun or wind,” making solar or wind power impractical.

For his part, Harrop believes TENGs could find their sweet spot in small ultrahigh frequency communications devices of the future. “As years roll by, the world of electronics will need only a whisper of power,” he says. “In that world, [triboelectrics researchers] are the knights on the white horse.”

Wang points out that TENGs entered the scene less than a decade ago. Carbon nanotubes and quantum dots have been around for three decades, he says, and products based on those technologies are still elusive. He has been showcasing the technology’s potential to academics, companies, and funding agencies. “People in other fields have to know this is a new scientific invention they can utilize in their product design or tech development,” he says. “That’s why I talk about it so much. It’s the fastest growing field in materials science and nanotechnology. I hope government agencies realize that.”

Whether practical devices emerge in the next few years or not, he says, triboelectrics offer an excellent opportunity to generate novel ideas and materials, and a new paradigm for harvesting energy from a variety of mechanical sources. It’s a field ripe for discoveries by chemists, materials scientists, physicists, and engineers. “This is the first time organic materials have been used for mechanical energy conversion,” Wang says. “People should have confidence in this technology. The more you work on it, the more you see how magical it is.”

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