Understanding how ions flow in and out of the tiniest pores promises better energy storage devices

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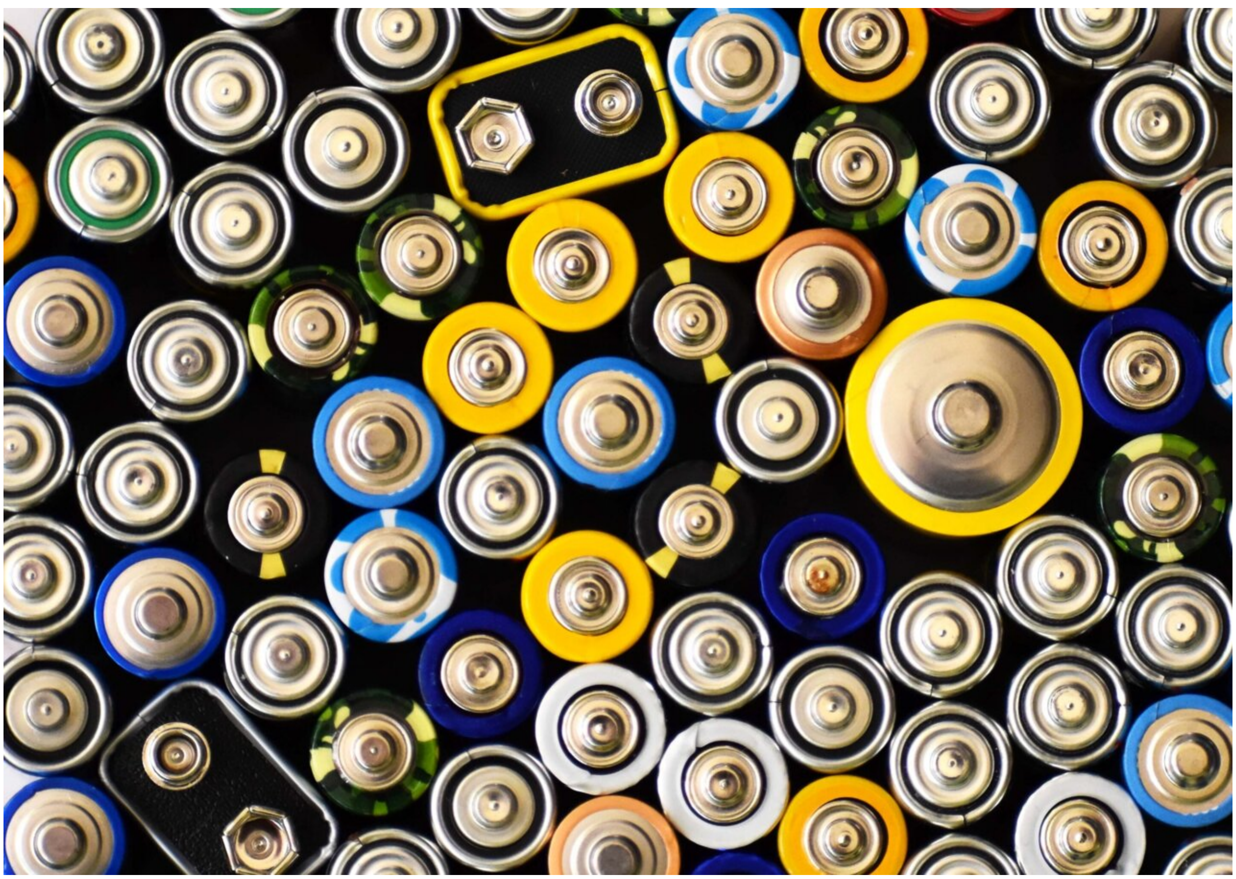

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Modern life relies on electricity and electrical devices, from cars and buses to phones and laptops, to the electrical systems in homes. Behind many of these devices is a type of energy storage device, the supercapacitor. My team of engineers is working on making these supercapacitors even better at storing energy by studying how they store energy at the nanoscale.

Supercapacitors, like batteries, are energy storage devices. They charge faster than batteries, often in a few seconds to a minute, but generally store less energy. They're used in devices that require storing or supplying a burst of energy over a short span of time. In your car and in elevators, they can help recover energy during braking to slow down. They help meet fluctuating energy demand in laptops and cameras, and they stabilize the energy loads in electrical grids.

Batteries operate via reactions in which chemical species give or take electrons. Supercapacitors, in contrast, do not rely on reactions and are kind of like a charge sponge. When you dip a sponge in water, it soaks up the water because the sponge is porous—it contains empty pores where water can be absorbed. The best supercapacitors soak up the most charge per unit of volume, meaning they have a high capacity for energy storage without taking up too much space.

In research published in the *Proceedings of the National Academy of Sciences* in May 2024, my student Filipe Henrique, collaborator Pawel Zuk and I describe how ions move in a network of nanopores, or tiny pores that are only nanometers wide. This research could one day improve the energy storage capabilities of supercapacitors.

All about the pores

Scientists can increase a material's capacitance, or ability to store charge, by making its surface porous at the nanoscale. A nanoporous material can have a surface area as high as 20,000 square meters (215,278 square feet)—the equivalent of about four football fields—in just 10 grams (one-third of an ounce) of weight.

Over the past 20 years, researchers have studied how to control this porous structure and the flow of ions, which are tiny charged particles, through the material. Understanding the flow of ions can help researchers control the rate at which a supercapacitor charges and releases energy.

But researchers still don't know exactly how ions flow into and out of porous materials.

Each pore in a sheet of porous materials is a small hole filled with both positive and negative ions. The pore's opening connects to a reservoir of positive and negative ions. These ions come from an electrolyte, a conductive fluid.

For instance, if you put salt in water, each salt molecule separates into a positively charged sodium ion and a negatively charged chloride ion.

When the surface of the pore is charged, ions flow from the reservoir into the pore or vice versa. If the surface is positively charged, negative ions flow into the pore from the reservoir, and positively charged ions leave the pore as they're repelled away. This flow forms capacitors, which hold the charge in place and store energy. When the surface charge is discharged, the ions flow in the reverse direction and the energy is released.

Now, imagine a pore divides into two different branched pores. How do the ions flow from the main pore to these branches?

Think of the ions as cars and pores as roads. Traffic flow on one single road is straightforward. But at an intersection, you need rules to prevent an accident or traffic jam, so we have traffic lights and roundabouts. However, scientists don't totally understand the rules that ions flowing through a junction follow. Figuring out these rules could help researchers understand how a supercapacitor will charge.

Modifying a law of physics

Engineers generally use a set of physics laws called "Kirchoff's laws" to determine the distribution of electrical current across a junction. However, Kirchhoff's circuit laws were derived for electron transport, not ion transport.

Electrons only move when there's an electric field, but ions can move without an electric field, through diffusion. In the same way, a pinch of salt slowly dissolves throughout a glass of water, ions move from more concentrated areas to less concentrated areas.

Kirchhoff's laws are like accounting principles for circuit junctions. The first law says that the current entering a junction must equal the current leaving it. The second law states that voltage, the pressure pushing electrons through the current, can't abruptly change across a junction. Otherwise, it would create an extra current and disrupt the balance.

Since ions also move by diffusion and not only by the use of an electric field, my team modified Kirchhoff's laws to fit ionic currents. We replaced voltage, V, with an electrochemical voltage, φ, which combines voltage and diffusion. This modification allowed us to analyze networks of pores, which was previously impossible.

We used the modified Kirchoff's law to simulate and predict how ions flow through a large network of nanopores.

The road ahead

Our study found that splitting current from a pore into junctions can slow down how fast charged ions flow into the material. But that depends on where the split is. And how these pores are arranged throughout the materials affects the charging speed, too.

This research opens new doors to understanding the materials in supercapacitors and developing better ones.

For example, our model can help scientists simulate different pore networks to see which best matches their experimental data and optimize the materials they use in supercapacitors.

While our work focused on simple networks, researchers could apply this approach to much larger and more complex networks to better understand how a material's porous structure affects its performance.

In the future, supercapacitors may be made out of biodegradable materials, power flexible wearable devices, and may be customizable through 3D printing. Understanding ion flow is a key step toward improving supercapacitors for faster electronics.

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