

diate detectable synchrotron emission at radio frequencies. The shock waves were too small and inefficient to get the job done in the first simulation. The second one reasonably reproduced the LOFAR intensities by including an additional, preexisting population of billion-year-old relativistic electrons that get accelerated by stronger merger-induced shock waves.

Several details about the mechanism still need to be worked out. Govoni and her colleagues do not know yet where the old relativistic electrons come from nor what mechanism fills the filament with

them. “It is important to understand whether the emission detected in the filament that connects Abell 0399 and Abell 0401 is a common phenomenon in the cosmic web,” says Govoni. “I hope that astronomers will soon find other magnetized filaments.”

Alex Lopatka

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A big step for nanoporous graphene provides a small step for desalination

Carbon-nanotube reinforcement and template-based etching help scale up membranes.

Residents of Cape Town, South Africa, planned their daily lives around a quota of 50 liters of water per person per day during the first months of 2018. As the city’s freshwater reservoirs dwindled, the municipal government rushed to bring a desalination plant on line. For-

tunately, heavy rains in June ended the region’s three-year drought. But the city’s water crisis illustrated a situation that’s becoming increasingly common in the face of growing populations and changing climate. The United Nations predicts that two-thirds of the world’s

population will face freshwater shortages by 2025.

The planet’s water is 97% seawater, which could in principle provide a steady freshwater supply. The first desalination plants were built in the 1960s, and now 20 000 facilities furnish water to 300 million people globally. Saudi Arabia produces 20% of the world’s desalinated water and, along with the United Arab Emirates and Kuwait, relies on desalination for daily life. Israel meets more than half of its domestic needs with Mediterranean seawater, and desalination provides a third of Melbourne, Australia’s municipal water supply. (See *PHYSICS TODAY*, June 2016, page 24.) The US Geological Survey estimates that the average American uses nearly 400 L of water per day. (The average water footprint per capita, which accounts for all goods and services consumed, is nearly 8000 L per day in the US.)

The original desalination plants were based on evaporating and then condensing seawater. Since 2005, however, most new plants have relied on reverse osmosis, and that method now accounts for 50% of the world’s desalination capacity. In reverse osmosis, hydrostatic pressure forces saline water through a semi-permeable membrane. Dissolved salts are blocked so that fresh water ends up on the other side. Reverse osmosis is the most energy-efficient desalination technology on the market. (See the Quick Study by Greg Thiel, *PHYSICS TODAY*, June 2015, page 66.)

Reverse osmosis, however, still suffers from poor freshwater recovery rates and high cost due to energy use. Some 40% of seawater and 80% of brackish groundwater can be recovered commercially as freshwater. The by-product is a briny concentrate. The plants require 3–10 kWh of electricity to produce 1000 L of fresh water. That’s the energy equivalent of running an electric clothes dryer several times. Most of that energy is used to move saltwater through the membrane.

Research into reducing that energy focuses on improving membrane efficiency and durability. An ideal membrane should be thin to maximize water permeability, selective to isolate particles and solutes, and mechanically robust to avoid breakage and leakage. It also needs to be meters in size for use in commercial desalination. Today’s reverse-osmosis

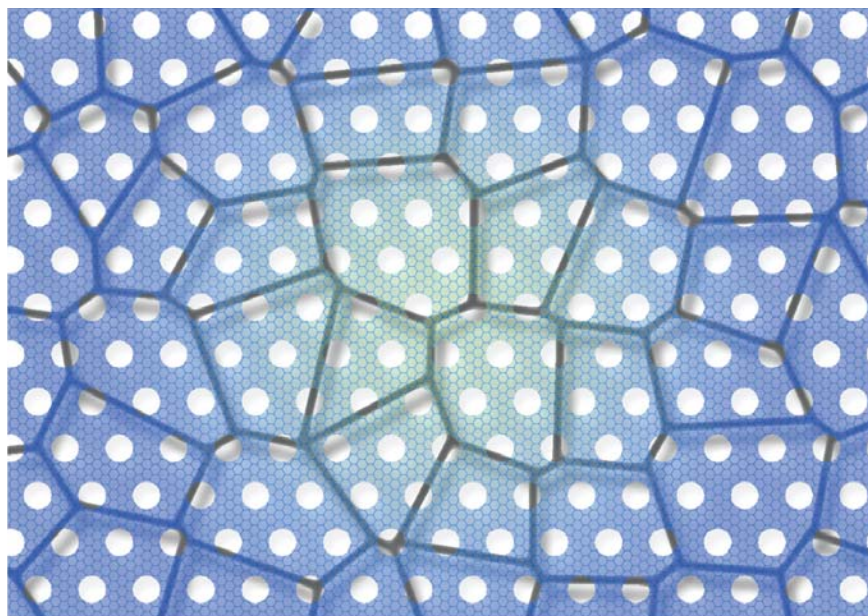


FIGURE 1. NANOPOROUS SINGLE-LAYER GRAPHENE is reinforced by a network of carbon nanotubes. The nanotubes create microscale sections, represented by the outlined polygons, that ensure the membrane’s structural integrity. (Adapted from ref. 1.)

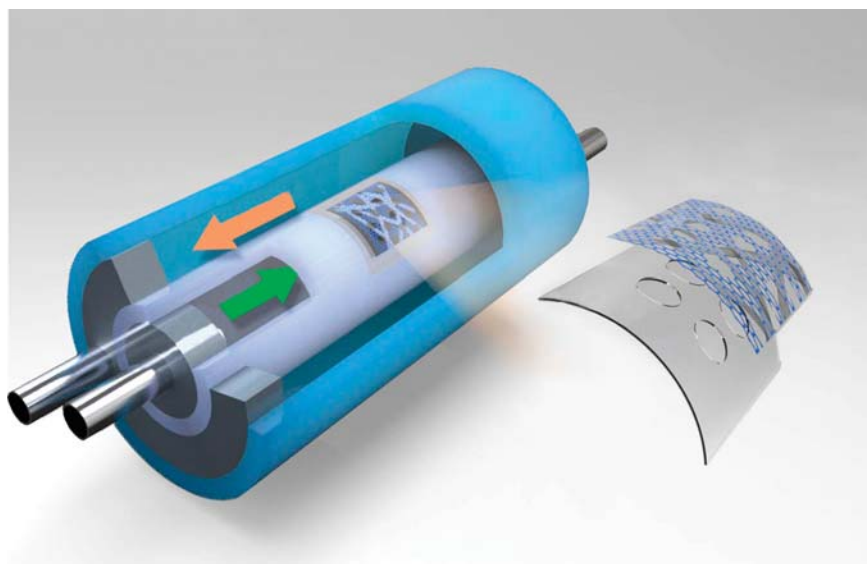


FIGURE 2. IN A TUBULAR DESALINATION MODULE, the nanoporous graphene membrane is fixed to a curved porous polymer substrate that is integrated into the innermost of two silicone tubes. Saline water (orange arrow) feeds into the aperture between the tubes and creates pressure on the membrane. Desalinated water (green arrow) is drawn out from the inner tube. (Adapted from ref. 1.)

plants mostly use polyamide composite membranes based on ones developed two decades ago. The membranes are easily clogged and require constant maintenance.

One alternative membrane being pursued by several groups around the world is a single layer of graphene perforated with an array of subnanometer-sized pores. The tiny pores trap salt but allow water molecules to pass freely. But nanoporous graphene tends to tear easily when its area is more than a few square microns. Now Xiangfeng Duan (UCLA), Quan Yuan (Wuhan University and Hunan University in China), and colleagues have designed a centimeter-scale freestanding, mechanically robust nanoporous graphene membrane, shown in figure 1, that filters salt and larger ions from saline solution and avoids fouling.¹

Big, strong, and freestanding

Graphene's chemical and mechanical stability, its flexibility, and its single-atom thickness make the material attractive for membrane technologies. Based on molecular dynamics simulations, David Cohen-Tanugi and Jeffrey Grossman at MIT predicted that nanoporous graphene could have a water permeability orders of magnitude greater than conventional reverse-osmosis membranes.²

For a single sheet of graphene etched with 0.45-nm-diameter pores, the simulations predicted 100% salt rejection.

Translating complete salt rejection from theory to practice meant finding a way to create pores without damaging the graphene's mechanical strength. Ivan Vlasiouk and colleagues at Oak Ridge National Laboratory did so by exposing a 50 $\mu\text{m} \times 50 \mu\text{m}$ square of defect-free graphene to short bursts of oxygen plasma.³ To test the sample's desalination performance, the researchers transferred it to a silicon substrate that had a hole in the middle 5 μm in diameter. The section of exposed membrane over the hole rejected 100% of salt in a pressure-driven flow.

Commercial desalination, though, requires membranes with areas of square meters, not square microns. Scaling to larger sheets is difficult because grain boundaries weaken graphene's mechanical strength, and pores further compromise the structural integrity. In one recent development, Rohit Karnik and colleagues at MIT carefully sealed rips and leaks before creating pores in a sheet of graphene.⁴ In another development by MIT researchers including Karnik, Piran Kidambi, and A. John Hart, a polymer support strengthened the membrane.⁵

Inspired by those advances, Yuan and her colleagues combined a series of

steps to develop a strong, freestanding, and flexible membrane. The researchers started with a single layer of graphene, which they grew by chemical vapor deposition to avoid grain boundaries. Then they reinforced it with a layer of carbon nanotubes. Finally, with a mesoporous silicon dioxide film as a mask, the researchers punched a grid of 0.3- to 1.2-nm-diameter holes using short bursts of oxygen plasma. The SiO_2 film had a uniform grid of pores several nanometers wide; removing the film left a precise network of pores in a strong, freestanding, 50-nm-thick membrane. As illustrated in figure 1, the nanotubes partitioned the membrane into micron-sized islands and acted as a supportive framework.

The researchers constructed a bench-top filtration system that pumped saline water across a flat section of membrane. The membrane blocked 85% of sodium chloride and up to 98% of larger-molecule solutes. It also withstood pressures up to 10 MPa, characteristic of commercial filtration systems, and achieved permeability two orders of magnitude higher than that of commercial membranes.

The carbon nanotube network had the mechanical strength and flexibility to endure large deformations without compromising structural integrity. A 0.36 cm^2 sheet of the membrane suspended on a frame supported 0.16 g without rupturing. Yuan also synthesized a graphene-only sample without the nanotube reinforcements. When she applied pressure to the center of the graphene-only version with a 0.5- μm -diameter pin, the sample quickly cracked into small pieces.

To improve desalination output, commercial membranes are usually rolled into a tubular structure to maximize their contact area with the water. Unlike previous graphene membranes, Yuan's is mechanically sound enough to bend into that configuration. She tested its performance in the module shown in figure 2. Despite some small cracks that formed during the bending process, the tubular membrane still removed 95% of the salt after 24 hours of operation.

Scrubbing salt from the wound

Commercial-scale nanoporous graphene may still be years away. Although Yuan's technique for drilling pores achieved an impressively narrow size distribution,

with 95% of the pore diameters between 0.5 nm and 0.75 nm, simulations indicate that pores greater than 0.55 nm in diameter may allow salt through. Additionally, larger sheets are more prone to larger-than-desired pores and defects. And growing graphene sheets by chemical vapor deposition makes the cost of a nanoporous graphene membrane much higher than that of a polymer membrane.

Even with improved membrane technology, desalination will still be plagued by environmental problems. Disposing of the concentrated brine left behind after desalination is no simple matter. Pumping it back into the ocean changes the region's salinity and harms ocean life. Also of concern are the copper and chlorine

that get added to seawater at various stages in the desalination process. They help to control bacterial growth and reduce corrosion but remain in the discharged brine.⁶

Rachel Berkowitz

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Teleportation for device-scale quantum computing

Trapped ions interact with help from an entangled pair of messengers.

A quantum computer will need a method to perform logic operations on qubits that are physically distant. Gate teleportation, proposed 20 years ago,¹ does just that. It takes an approach similar to teleporting a qubit (see the article by Charles Bennett, *PHYSICS TODAY*, October 1995, page 24) and uses entangled particles, or messengers, to teleport a logic gate that executes the operation. The messengers are entangled beforehand, and each one travels to a qubit and ropes it into the entangled state. Gate teleportation may also help deal with error propagation (see the article by John Preskill, *PHYSICS TODAY*, June 1999, page 24).

In a modern classical computer, a switch uses many electrons, $N \sim 10^5$ or more. Provided the number of electrons doesn't deviate by more than $\sqrt{N}$, the gate works flawlessly—typical failure rates are less than 10^{-18} . In a quantum logic gate, any error in the input carries over to the output, and the gate can't correct itself. The best isolated two-qubit quantum gate operations in trapped ions have an error rate of 10^{-3} . A quantum computation that enlisted more than a modest 1000 gates would always fail—without quantum error correction, that is.

To correct errors, a quantum computer needs redundancy: The more qubits encoding the same information, the less likely all, or even a majority, of them will err. A practical device would use many physical qubits to encode every logical qubit in the computation and require millions of physical qubits total. But a device that large can't have all its qubits in close proximity. Gate teleportation is one way for qubits to interact without the inherently slow process of migrating distant qubits together.

Now the Ion Storage Group at NIST in Boulder, Colorado, has demonstrated gate teleportation in trapped ions.² The experiment was led by Dietrich Leibfried, Andrew Wilson, and David Wineland. Gate teleportation serves as a test case for many necessary features of a trapped-ion quantum computing architecture that can be scaled to thousands or even millions of qubits (see the article by Ignacio Cirac and Peter Zoller, *PHYSICS TODAY*, March 2004, page 38).

Making it happen

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