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Physicists Go Out on a Limb to Advance AI Computing

UC San Diego research team uses quantum materials to create "neural trees" that mimic brain synapses

A neuromorphic computer—one that is inspired by and works like a human brain—is the goal of many scientists around the world. Collaborative teams supported by the U.S. Department of Energy (DOE) are working to develop such an energy-efficient device from quantum materials. To achieve this form of artificial intelligence (AI), researchers must create manufactured synapses—structures in the brain that enable memory and learning over long periods of time. The DOE-supported Energy Frontiers Research Center, Q-MEEN-C, is leading this effort at UC San Diego.

In a new paper published in *Nature Communications*, physicists Alex Frano, Oleg Shpyrko and Ivan Zaluzhnyy of UC San Diego, along with collaborators from Purdue University, Argonne National Laboratory, University of Louisville, KY and Brookhaven National Laboratory, explain how the brain's synapses encode memory by adapting their resistance, or "weight," to electrical stimuli. While a synapse's resistance increases or decreases with stimuli over the life of its host, it will not change to the point of breaking the neural circuit. This is because evolution developed a mechanism—a branch—to keep the circuit stable.
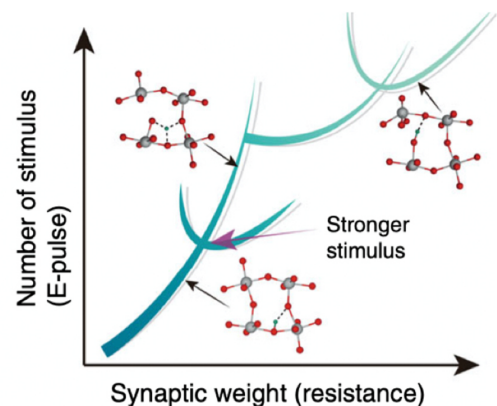

Figure 1. A schematic of the tree structure showing synaptic strength (resistance) as function of number of stimulus (electric pulses). Figure courtesy of Q-MEEN-C research team

If the stimuli change in pulse, intensity or duration, however, the trajectory changes into another branch. After many such stimuli changes, the synaptic weight trajectory has many branches and thus many "learned" states—allowing the host a lifetime of learning—a tree of knowledge of sorts.

Similar to decision-tree algorithms in math, this tree-like structure for sustaining memory has been impossible to replicate in real materials. But in their paper, titled "Perovskite Neural Trees," the national research team demonstrates the ability to generate tree-like trajectories of the electrical resistance of a material.

"We were so surprised to discover how the resistance trajectory of our devices mimics those of actual brain synapses," said Frano. "The ability to make 'neural trees' or 'decision trees' in hardware is very exciting."

The scientists explain in their paper that the difficulty has been finding real materials that can host multiple states that can each be uniquely identified electrically and are capable of learning. They overcame these challenges, however, by discovering a material that displays these properties.
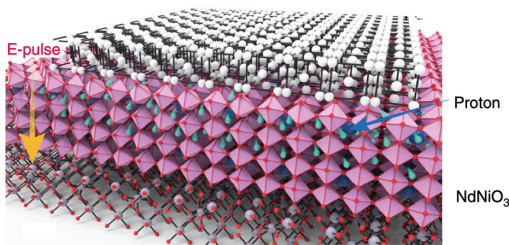

Figure 2. A schematic figure of the perovskite nickelate. Applying electric field pulses can move the protons in the lattice, thus modulating the device resistance in a systematic manner. Figure courtesy of Q-MEEN-C research team

"We show they can operate safely without catastrophic breakdown, and we demonstrate that they can learn. The results open up a new dimension of safe hardware for AI and neuromorphic computing," Frano said.

In their study, the researchers exercised atomic-scale control over proton migration in a nickel-oxide thin film subject to nanosecond electric pulses (see Figure 2). The resistance of these materials is highly sensitive to proton doping (i.e., one proton addition per chemical formula leads to ~10 orders of magnitude change in electrical resistance) and electric field pulses (the resistance changes upon applying electric field pulses). The latter occurs through the migration of protons relative to the electric field.

The team at UC San Diego applied a novel experimental technique of focusing an X-ray beam down to 20 nanometers, so they could "visualize" how the protons move around the sample as they create new tree branches. According to the researchers, the quantum mechanical amplification effect from proton drift enables a vast number of tree memory states that are dynamically programmable using electrical pulses. Together, these aspects form the basis of neuromorphic hardware synapses.

"Our team was excited to literally 'see' how the migration of protons inside the material gives it the chance to develop a resistive trajectory, or 'branch,'" said Frano. "Furthermore, different pulses reorganize the protons in different configuration, yielding another branch. The sheer

ability to detect the migration of light hydrogen protons at the nanometer scale was incredibly exciting to us."

The impact of these findings spans a range of fields.

"On the one hand, these can be now implemented into architectures of neuromorphic hardware. For instance, software/hardware hybrid systems can now be designed. On the other hand, now that we understand better the physical mechanism by which we can create these artificial neural trees, we can explore other materials that can allow us to do that," Frano said. "Finally, the technique we developed to visualize the motion of protons, we can use it to understand other relevant phenomena like electromigration and phase separation in materials."

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