COMPUTATION'S NEW LEAF

Plants may be calculating creatures

BY ERICA KLARREICH

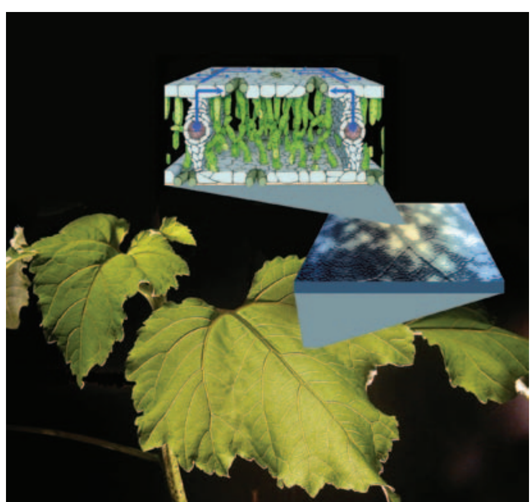
To most people, the word *computer* conjures up an image of a PC sitting on a desktop. According to a new study, however, complex computations may also be underway in another bit of office equipment: the potted plant that brightens up the windowsill. Plants may perform what scientists call distributed emergent computation. Unlike traditional computation, in which a central processing unit carries out programs, distributed emergent computation lacks a central controller. Instead, large numbers of simple units interact with each other to achieve complex, large-scale computations.

Although the plants don't add, subtract, multiply, or divide, they do seem to compute solutions to problems of how to coordinate the actions of their cells effectively.

Many biological systems appear to carry out this type of distributed computation—for instance, ant colonies, nervous systems, and immune systems. One favorite example among biologists is slime molds, which exist for most of their lives as single-celled, amoebalike creatures. When their food supply runs dry, they somehow figure out, through local signals between cells, how to swarm together into a sluglike, multicellular organism that produces the spores that give rise to the next generation.

Pinning down these computations in precise ways has proved elusive.

The new work with plants is "the first experiment I know of where you can actually see what looks like a distributed computation taking place in a natural system," says Melanie Mitchell, who studies distributed emergent computation at Oregon Health and Science University in Beaverton. "That's very exciting."



PATCHY INTERACTIONS — In the top image, a leaf's pores (black passageways to the surface of the leaf) allow in carbon dioxide. Computations arising from interactions between these pores may govern the formation of patches of open and closed pores. A chlorophyll fluorescence image (middle image) shows patches consisting of thousands of open pores (bright areas) or closed pores (dark areas).

MOTT

A DELICATE BALANCE Plants may use computation to figure out how wide to open pores in their leaves, researchers propose in the January 27 *Proceedings of the National Academy of Sciences*. The leaf pores, also called stomata, open to allow in carbon dioxide, which plants need for photosynthesis. However, open pores also let out water and so may dehydrate the plant. To balance these competing factors as environmental factors change, plants constantly adjust how many and how widely their pores are open.

The way that plants achieve this balance has been a mystery. There's no brain to coordinate the tens of thousands of pores, and individual pores seem to have no way of knowing what distant pores are doing.

At first, biologists thought that each pore simply decided independently what action to take. About 10 years ago, however, researchers noticed that large patches of pores frequently open and close in concert. More recently, Keith Mott, a biologist at Utah State University in Logan, discovered that over minutes, these patches of synchronization move about the leaf, often displaying complex dynamics.

He described these observations to physicist David Peak, a colleague at Utah State. They reminded Peak of patterns that turn up in cellular automata, a kind of distributed emergent computer.

"It occurred to us that the patterns could be symptomatic of a distributed emergent computation," Mott says.

SIMPLE AND COMPLEX Mott and Peak next investigated whether there was more to the seeming similarity between the behavior of leaf pores and of cellular automata. A cellular automaton consists of a collection of units called cells, each of which can be in one of several states. Over time, the cells change their states according to rules that depend on their current states and those of their neighbors.

The best-known cellular automaton is the Game of Life, invented in 1970 by British mathematician John Conway, now at Princeton University. The game consists of a grid of cells, each of which is considered to be either dead or alive. At each time step, some cells switch state according to simple rules. For instance, a live cell with at least four living neighbors dies of overpopulation. Even though each cell is influenced only by nearby cells, complicated global patterns can emerge.

In 2002, theoretical physicist Stephen Wolfram argued in his book, *A New Kind of Science* (Wolfram Media), that cellular automata may underlie nearly all phenomena, from the physics of elementary particles to life and intelligence (*SN: 8/16/03, p. 106*).

Most scientists don't subscribe to such a sweeping vision, Mitchell says, but cellular automata are being applied to a wide range of questions. They have been used, for instance, to process images and to model earthquakes, traffic patterns, and tumor growth.

In a cellular automaton with thousands of cells, it can be virtually impossible to predict which kinds of global behaviors will emerge from which local rules. "It would be like trying to figure out what a computer is doing by looking at how voltages flicker up and down on the motherboard," Peak says.

In the mid-1990s, Mitchell—together with James Crutchfield of the Santa Fe Institute in New Mexico and Rajarshi Das of the Thomas Watson Research Center in Yorktown Heights, N.Y.—tried a different approach to understanding cellular automata. Rather than design specific rules to produce a certain global behavior, the team used a genetic algorithm—which exploits the principles of Darwinian natural selection—to evolve cellular automata that behave as the team had stipulated.

For instance, using cells that could be either black or white, the team produced an automaton in which the cells flash in unison, alternating between black and white. The team started out with automata that each had random rules, then selected the automata that came closest to the desired behavior. They permitted the surviving automata to exchange some rules with each other, mimicking sexual reproduction, and introduced small random mutations into the resulting rules. After many of these generations, the resulting automata behaved as the researchers had originally specified.

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This evolutionary success hints at how living creatures might have developed cellular automata, if indeed they have. Out of all the possible interactions among living cells, evolution may have selected interactions that give rise to useful computations.

LEAF DYNAMICS Peak, Mott, and their collaborators compared the movements of patches of synchronized pores in cocklebur leaves to those of patches of black and white cells in the automata that Mitchell's team studied. Using fluorescence imaging, they tracked the flux of open and closed pores on a leaf over 8-hour periods.

Patches of synchronization ranged in size from just tens of pores to tens of thousands of pores, and the patches moved about the leaf over the course of minutes, the team found. The researchers also measured what they call the "waiting time" between the appearance of successive patches in each pixel of the fluorescence images. The distribution of these waiting times, they found, obeyed a simple mathematical law known as a power rule.

The scientists next compared the statistics of patch sizes and waiting times to those of corresponding data in the cellular automata. "The dynamics of the unfolding computation [in the cellular automata] looks statistically identical to what we see in the patchiness of leaves," Peak says.

The opening and closing of leaf pores is a subject that has been "studied to death," says botanist Michael Frohlich, of the Natural History Museum in London. "It's amazing that something this surprising is found in a field that has been studied so hard for so long."

Just which local rules might give rise to the global patterns of open and closed pores is a puzzle, Mott says. "The rules are the single hardest thing to deduce," he says. Instead of trying to guess the rules by working backward from the global behavior of the leaf, Peak and Mott are trying to create a computer model whose rules take into account the ways that leaf pores might influence their neighbors through hydraulic pressure and other mechanisms.

The real test, Peak says, will be whether their model produces the same kinds of patch dynamics and carbon dioxide uptake that biologists have observed in leaves.

Cellular automata may give biologists a new framework for understanding how small-scale interactions can give rise to global characteristics of an organism. "We have a wealth of information about cell-to-cell interactions, but the question is: 'How do these interactions produce large-scale behavior?'" Mott says. "Perhaps distributed emergent computation will provide us the tools to make that jump." ■