In principle, at least, QCA cells do away with all of these problems. Each cell consists of a square arrangement of four quantum dots—minute islands of a material that has a higher affinity for electrons than the surrounding material. Two electrons inhabit each cell. Their mutual repulsion forces them into opposite corners, like boxers between rounds; the two possible configurations stand for binary 0 and 1. The electrons rely on tunneling to move from dot to dot, which they do under the influence of adjacent cells. Like neurons in the retina of the eye, they process information by interacting with their neighbors rather than by sending impulses to some central location, which is why they are called cellular automata.

A. ORLOV, *ET AL.*

Tunnel vision. Electrons tunnel between aluminum islands (indicated by red circles) microns apart in a quantum-dot cell.

When a cell at the end of a row is forced into state 1, for example, the next cell will flip into the same state, since that ensures the maximum distance between electrons in the two cells. The rest of the cells will quickly fall into line, passing the 1 down the "wire." Such wires could be intertwined to perform more complicated operations in which one state can be contingent on several others (see diagram).

Since each signal passes down the line without any current, little heat is generated, and because each cell passes information directly only to nearby cells, which can then send the results to the next cluster for further processing, the interconnection problem is eased. And the smaller the dots are made, the better they confine electrons, keeping thermal fluctuations from dislodging them; indeed, extremely small cells could operate at room temperature. "Things only get better as you shrink them down," says Lent. "It could go down to molecular levels."

But would this theorist's dream fall to pieces in a real experiment? Some critics had predicted that the electrons would leak away through interactions with defects and free charges in the surrounding material, rather than remain stably confined. Others had questioned whether the dots could be made accurately enough for the tunneling to work as designed.

To test the scheme, the Notre Dame group used a tightly focused electron beam to lay out a single QCA—an array of four aluminum dots on a silicon dioxide surface. They put the device through its paces by using voltage biases to force electrons either up or down on one side of the cell (call it the right side) and checking whether the electrons on the left side responded. They found that electrons did move to the opposite corner on the left side, remaining there for periods of minutes. "We can sit there and watch it," says coauthor Greg Snider, "and, no, [the charge] doesn't leak off."

In a complicated set of measurements in which one pair of dots actually probed the other, Snider and co-workers also determined the electrical potential—an indicator of how charges are distributed—on the left pair as the switching took place. The fluctuations in the potential compared favorably with theory, suggesting that electrons really were tunneling between dots and were not, say, being drawn randomly from defects in the crystal lattice. "I think it is a very important breakthrough," says Tamás Roska, a professor at the Computer and Automation Institute in Budapest. "These are not easy experiments," adds UCSB's Petroff. "But I have no doubt [that the switching was observed]."

He notes, however, that QCA's longer term prospects remain controversial because of questions about how well large systems of the dots will function—even if they can be accurately fabricated in much smaller sizes, which would require new techniques. Rolf Landauer of IBM's T. J. Watson Research Center has persistently questioned whether "exactly two" electrons will stay confined in each cell—crucial for such a device to work properly—and whether slight defects in the system will play havoc with its computations. A more vociferous critic, Supriyo Bandyopadhyay of the electrical engineering department at the University of Nebraska, Lincoln, says "fundamental flaws" in the scheme will prevent the arrays from working even if they are built perfectly. For example, the system may get permanently stuck at a wrong answer on its way to the right one, he and his collaborators say, as the electron states reach an impasse akin to traffic gridlock on downtown streets.

Lent says the group has addressed some of these doubts and is studying others. His detailed calculations show, for instance, that running an array at slightly slower than its maximum speed—so-called "adiabatic switching," an approach suggested by Landauer—gets around the wrong-answer problem, just as conservative drivers have a slower commute, but cause fewer traffic snarls than heavier-footed motorists. Still, he says, "One is rightfully concerned about overselling a technology." Whether the click clack of his group's dots will turn out to be first footsteps leading computer science into the realm of the very small remains to be seen.

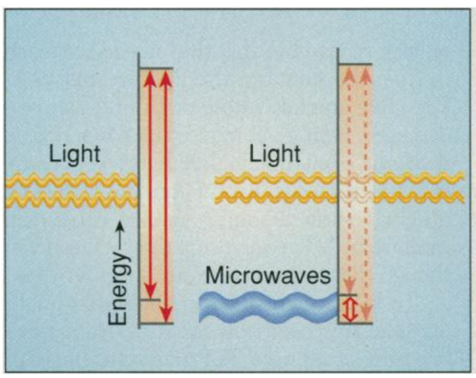
–James Glanz

PHYSICS

Microwaves Steal the Blush From Ruby

Rubies are red, and they usually stay that way. But in the 28 July *Physical Review Letters*, researchers at Wayne State University in Detroit report that they have made rubies a little less red and more transparent with nothing more than a magnet and a bath of microwaves.

The feat, called electromagnetically induced transparency, had already been demonstrated in gases. But "this is the first work in solid-state materials," says electrical engineer Yang Zhao, one of the researchers. He and others say it might eventually lead to more efficient lasers and to optical switches for computers.



LIZ CARROLL

A lock on absorption. Electrons that normally absorb light by jumping to a higher energy level (left) are stymied when microwaves couple two lower levels.

Color, in rubies and most other materials, arises because electrons in the material absorb specific wavelengths of light. The absorption takes place when a photon of light with the right energy kicks an electron from a low-energy level into a higher one. To clear a path through an absorbing material, electrons must be prevented from jumping up to the higher energy level—not an easy task.

Researchers working with gases had already demonstrated a way to shackle these jumping electrons: Use electromagnetic fields to link the lower energy level—the electrons' jumping-off point—with another level at a similar energy. To apply this strategy to rubies, Zhao and his colleagues cooled the material to 2.4 degrees above absolute zero to "sharpen" the energy levels. Then they placed it in a magnetic field, which split each of the energy levels into two closely spaced levels through what is known as the Zeeman effect. Each pair of levels corresponds to a particular direction of electron spin—up or down.

Once Zhao and his colleagues had split the energy levels, they applied a microwave field that had just the right energy to "couple" two of the lower energy levels by flipping the electrons' spins back and forth, forcing them to jump between the levels. By providing two competing paths for electrons to jump from a lower to a higher level, the coupling stymied the transition. "When you have light taking two paths and hitting a screen, at certain parts of the screen, the light cancels out," explains Scott Shepard, a physicist at Texas A&M University in College Station. "This is a very similar canceling out; the wave functions cancel." Because the electrons can't jump into the high-energy band, the ruby fails to absorb the wavelengths of light that would normally do the kicking.

The team was able to reduce absorption by about 20%. Other researchers have gotten much better results in gases. But "work in atomic vapors mainly demonstrates the principle," Zhao says: "Work in solid state may lead to real devices." Atac Imamoglu, a physicist at University of California, Santa Barbara, agrees. Even though the work is at a very early stage, he thinks that "several avenues [of possible application] are interesting." The ability to vary the transparency of an optical medium, he says, might be useful for storing bits in a quantum computer or creating switches for an optical computer. By cutting down on the amount of light absorbed in a laser's light-generating medium, he says, it could also lead to lower powered lasers.

–Charles Seife

Charles Seife is a writer in Riverdale, New York.

NEUROBIOLOGY

Schizophrenia Clues From Monkeys

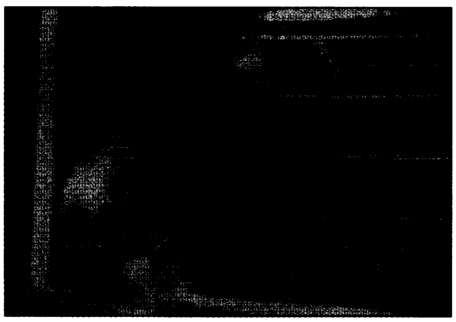
For decades researchers have tried, without much success, to stitch the patchwork of schizophrenia symptoms into a single picture. One in every hundred people suffers from this brain disorder, with manifestations that range from delusions and hallucinations, to lack of behavioral inhibition and cognitive problems—such as inability to make even simple decisions. Now, researchers from Yale University School of Medicine in New Haven, Connecticut, have taken a step toward understanding some of the brain changes involved in this disease.

On page 953, pharmacologist Robert Roth and his colleagues report that they can create cognitive problems in vervet monkeys by treating the animals with phencyclidine (PCP), a drug of abuse better known as "angel dust." Other researchers have studied how the drug affects behavior in animals, but they have not, for the most part, tested the animals on complex tasks such as those impaired in schizophrenia. What's more, the Roth team's results suggest that the more severe the cognitive deficits, the bigger the changes in dopamine—a neurotransmitter already known to be involved in schizophrenia—in the prefrontal cortex of the monkeys' brains. And they found the monkeys' problems can be partially reversed by a drug used to treat the condition in humans.

"I'm quite impressed," comments psychopharmacologist Klaus Miczek from Tufts University in Boston. "The combination of a complex behavioral test and the neurochemistry is very nice." Indeed, comments John Hsiao, a psychiatrist at the National Institute of Mental Health in Rockville, Maryland, "depending on how good a model [the PCP-treated monkey] is, this could be a tremendous advance." Studies of these monkeys may help clarify why cognitive problems arise in schizophrenia patients and could also help researchers evaluate therapies for improving cognitive function.

The Yale group decided to try PCP on the monkeys, because they knew the drug causes schizophrenic symptoms in people, particularly when used repeatedly. For the experiments, J. David Jentsch, a graduate student in Roth's lab, administered PCP twice daily to 15 monkeys for 2 weeks. A week later, he evaluated six of the animals—and an equal number of controls—with a behavioral test, in which each monkey was presented with a transparent cube that contained a slice of banana and was open on one side.

Instinctively, both PCP-treated and untreated monkeys grabbed for the banana by reaching straight for it. They all succeeded as long as the cube opening faced them. When the cube was rotated, untreated monkeys



JANE TAYLOR/YALE UNIV.

Monkey do. PCP-treated monkeys can't figure out how to retrieve a treat from this cube.

quickly figured out that they needed to reach in from the side. But the PCP-treated monkeys, like animals whose prefrontal cortex is damaged, kept grabbing for the banana from the front, even though their hands kept banging into the cube wall. People with schizophrenia show a similar lack of behavioral inhibition. "They can't stop themselves, even though they know it is wrong," says Jentsch.

To look for chemical changes that might underlie this behavior, the Yale team sacrificed the other nine PCP-treated animals, as well as four controls. Then, to get an indication of dopamine usage, they measured the amounts of both dopamine and one of its breakdown products in various regions of the prefrontal cortex. The PCP treatment proved to be "very selective" in its effects, Roth notes, reducing dopamine usage in only two sections. One was the dorsal-lateral prefrontal cortex, which is responsible for working memory—essential if the monkey is to remember that it had already tried to grab the banana from the front. The other section was the prelimbic cortex, a section of the brain thought to control behavioral inhibition. "There's a direct and significant relationship in the degree of inhibition of dopamine [usage] and the degree of cognitive impairment," says Jentsch.

In a final test of the PCP monkey as a model for schizophrenia's cognitive symptoms, the Yale team evaluated the effects of clozapine, a drug used to treat the condition, on the surviving PCP monkeys. The drug improved their ability to figure out how to get the banana out of the cube, they report. This result highlights the power of using the PCP-treated monkey to study these deficits, says Roth. "There are other animal models of prefrontal cortical dysfunction, but they are not pharmacologically reversible," he points out.

The new work also fits with the growing view that dopamine's role in schizophrenia is more complicated than originally thought. Because many antipsychotic drugs block dopamine receptors, decreasing dopamine function, researchers once thought the symptoms were caused by an excess of this important nervous-system chemical. But this and other recent work suggest that while dopamine concentrations increase in some brain areas in schizophrenia, they decline in others—a result similar to what happened in the prefrontal cortex of the PCP-treated monkeys. "You can have both high and low dopamine at the same time," says Jentsch.

The Yale group hopes that continued work with the PCP-treated monkeys will lead to a better understanding of how dopamine is affected in the animals. And from those findings, says Jentsch, "we may be able to extrapolate what's going on in schizophrenia."

–Elizabeth Pennisi