can reliably store analog information as electrical charge, enabling it to keep track of previous signals fed to it. These new transistors should open the way to building systems that can learn from experience, as neural-net software does, but more efficiently, because the hardware itself is learning.

ETU/UNIV. OF ADELAIDE

Collision avoider. Toy cars, one equipped with a silicon retina that detects a second car approaching from behind, and designer Alireza Moini.

Labs around the world are already exploiting AVLSI to build silicon noses, ears, and especially eyes. At the University of Adelaide in Australia, Alireza Moini and his team have built a succession of "bug-eye" chips, using a design abstracted from insect eyes. One variant senses motion by tracking regions of changing light intensity—an ability that could lead to collision sensors for cars. Andreou, together with Kwabena Boahen at Caltech, has built the most advanced silicon retina yet, with a resolution of 210 by 230 pixels. And Tamás Roska and his team at the Computer and Automation Institute in Budapest, Hungary, have produced a programmable "visual microprocessor" that can analyze a scene and swiftly pick out patterns for applications such as medical diagnosis.

In Zurich, Paul Verschure and Giacomo Indiveri are working on a silicon-retina–controlled robot that can follow a line across the floor of their laboratory. "We showed that we can reliably track an edge, independent of colors and textures of the surface," says Verschure. Their robot can stay on course for more than 100 meters—"the time we got fed up looking at the device doing the same thing."

Mimicking biology does have its disadvantages. Relying on continuously varying electrical states rather than the clearly defined ones and zeros of digital computing means that tiny variations in the components may cause them to respond differently to identical inputs. In silicon retinas, for example, pixels may vary in performance by as much as 20%. The brain can interpret sensory information reliably in spite of that kind of variability, thanks to the huge numbers of interconnections that allow it to smooth and correct data, says Koch.

Mimicking those dense interconnections is the field's other great challenge. "What the brain has that we do not have is connection technology," says Koch. Each cubic centimeter of the brain contains 100,000 cells and 2 kilometers of wiring, enabling each neuron to talk to 10,000 others. "We don't have that kind of technology right now." In the future, optical interconnections, relying on pulses of light that can crisscross freely, could solve the wiring problem. And nearly 10 years ago, the late Misha Mahowald at Zurich proposed a scheme to reduce the number of physical connections needed in a neuromorphic system. In her method, extended in a collaboration with Douglas, silicon neurons exchange addresses rather than actual pulses. A sender neuron communicates with its target over a common line linking many neurons, telling it to expect a signal from a particular address. The receiving neuron then recreates the signal, as if it had come over a dedicated line from the sender.

Even if they solve these problems, neuromorphic engineers are under no illusions about displacing conventional computing technology, which is unbeatable for number crunching. Ultimately, they hope to create neuromorphic sensors that can feed their readings of the world around them to digital electronics for subsequent processing, says Koch, who, for example, envisages cameras with a neuromorphic "seeing end" feeding a conventional data-processing unit. Says SUI's Etienne-Cummings: "If engineers can mimic the benefits of biological organisms while capitalizing on the speed of [digital] electronics, the resulting computational systems can be very powerful."

–Andrew Watson

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ARTIFICIAL LIFE

After 50 Years, Self-Replicating Silicon

The workings of living things are an inspiration to avant garde computer scientists, but so far the simple act of reproduction has them stymied. In fact, it's defeated them since the late 1940s, when the legendary computer scientist John Von Neumann first tried to see whether a computer could be made to reproduce. He managed to conceptualize a self-replicating computer using cellular automata—identical computing devices arranged in a checkerboard pattern that change their state based on the states of their nearest neighbors. But his scheme called for an enormously complicated device made of millions of 29-state cellular automata, if not more. "It was so big," says Stanford University's John Koza, "nobody has ever even done a simulation."

Now researchers at the Swiss Federal Institute of Technology in Lausanne are on the verge of achieving in practice what Von Neumann could only work out in theory—and they are doing so in a far smaller system. In the September issue of the journal *Robotics and Autonomous Systems*, Daniel Mange and his colleagues report that they have made a self-repairing, self-replicating version of a specialized computer. It's able to perform only one specific task, but they hope to do the same soon with a "universal" computer—a necessary step, says Koza, toward creating computers that truly mimic life by reproducing and evolving.

Like Von Neumann's scheme, the Swiss system is based on cells of identical processors, which they call "biodules." Each cell contains a random-access memory and a single field programmable gate array, which is a collection of circuits that can be rewired by software, allowing it to assume new functions (see p. 1931). The biodules are laid out in a two-dimensional array, with a "mother cell" at one corner. Each one is programmed with an artificial chromosome—a string of bits that encodes all the information necessary for all the cells to function together as a computer.

Mange explains that each cell uses the mother cell as a reference point to calculate its position in the array, extracts from the bit string the information that a cell at that position needs to carry out its particular functions, and wires itself accordingly. The resulting computer can perform just one task: checking a string of parentheses to see if every left parenthesis belongs to a closed pair.

The system is able to repair itself by enlisting spare cells that sit off to one side of the working array. When a cell is identified as faulty, its entire column is deactivated. Then the functions of each column are shifted one column over, so that a spare column takes over the function of what used to be the last working column of the computer. Mange suggests that such a system might have applications in avionics, for instance, for computers that require extraordinary fault tolerance, but he admits that there is a "rather high" price to pay in efficiency: the need to store the complete "genome" in every cell. "It's the same price biology agrees to pay with every living being to have a very safe architecture," he says.

Self-replication is an extension of the same idea. Mange and his colleagues have shown that with enough spare cells in the array, all of the working cells of the computer can simply copy themselves into a new set of cells. Moving on to a self-replicating universal machine should be relatively easy, says Mange. "We should be able to realize the original dream of Von Neumann in the very near future," he says.

–Gary Taubes