ORDINARY HARDWARE DOES THE SAME OLD JOB UNTIL IT WEARS OUT, WHEREAS EVOLVABLE HARDWARE ADAPTS ITSELF TO A CHANGING TASK

A new species of hardware

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AS YOU READ THESE LINES, YOU ARE USING A POWERFUL set of devices—including eyes, hands, and a brain—all of which share a fundamental characteristic: they are the products of the random mutations and genetic mixing of Darwinian evolution. As anthropologist Melvin Konner wrote not long ago: "Neuroanatomy in any species—but especially in a brain-ridden one like ours—is the product of a sloppy, opportunistic, half-billion-year [process of evolution] that has pasted together, and only partly integrated, disparate organs that evolved in different animals, in different eras, and for very different purposes" [see 'To Probe Further, p. 64].

This single sentence, which captures the basic workings of natural evolution, also contains all the qualifiers (sloppy, opportunistic, pasted together, only partly integrated, and so forth) needed to describe "bad" engineering. And yet, between Man and Nature, Nature is the more ingenious engineer of the two. The proof is right before your eyes. Part of the proof is, in fact, your eyes, as well as the other organs that make up your body.

If nature is so successful a designer, why not simulate its workings in an engineering setting? By using a computer to evolve solutions to hard problems? Researchers pursuing this idea in the 1970s and 80s gave birth to the domain of evolutionary computation. Four decades later, the domain is flourishing, both in industry and academia, presenting what may well be a new approach to optimization and problem-solving.

Published in 1859, Charles Darwin's On the Origin of Species by Means of Natural Selection shook the foundations not only of science but also society at large. Now, with new uses for the evolutionary model coming into being, researchers and scientists are beginning to create hardware that can grow and improve itself over time, evolving steadily as it finds new and better ways to do the tasks it has set before it. And the
results may have as much of an impact as Darwin's findings did.

THE ORIGIN OF A NEW SPECIES

Of course, Darwin's theory of random mutation under selective pressure has in effect been utilized for much more than 40 years. Hantman and has practiced evolutionary engineering for thousands of years, in the guise of plant breeding and animal husbandry. The move from the natural world to the digital is but a small step further.

A computer can run the evolutionary process all by itself once software has been used to define the thing to be evolved and to create a pool of initial specimens. The software evaluates the existing generation of specimens in accordance with a predefined fitness criterion, then breeds the next generation by combining and mutating—in line with the laws of probability—the fittest of the current candidates. This process of fitness-based reproduction is repeated in the hope of finding a solution that meets the user's criteria of acceptability. [See “What is evolutionary computing?” by David Fogel, IEEE Spectrum, February, pp. 26–32.]

Essentially, evolutionary computation is a software affair, carried out as a simulation on ordinary hardware such as a PC or workstation. However, it is also possible to take evolutionary algorithms similar to those used by software and embed them directly into hardware. These devices, known as evolvable hardware, are the focus of a growing endeavor to build autonomous, adaptive, and fault-tolerant electronic systems, the present targets being, among others, computers, controllers for medical prostheses, and graphic printers, among which more will be said later.

The field was officially inaugurated only five years ago, when Eduardo Sanchez and Marco Tomassini from the Swiss Federal Institute of Technology in Lausanne organized the first Conference on Evolvable Hardware in that city. In the preface to the conference proceedings, entitled Towards Evolvable Hardware, they outlined the field's mission: "The remarkable increase in computational power and, more recently, the appearance of a new generation of programmable logic devices have made it possible to put into actual use models of genetic encoding and artificial evolution; this has led to the simulation and ultimately the hardware implementation of a new breed of machines."

"...We have crossed a technological barrier beyond which we can no longer meet content ourselves with traditional approaches to engineering design; rather, we can now evolve machines to attain the desired behavior." Sanchez and Tomassini went on to state boldly that "...we are witnessing the emergence of a new era, in which the terms 'adaptation' and 'design' no longer represent opposing concepts."

A VITAL DISTINCTION

Engineers using evolutionary computation depart from the classical design route, and allow the computer to search automatically through the 'space' of all possible designs. But just how can evolution be used to make physical devices evolve—how is evolvable hardware obtained? The simple answer is: make some desired behavior of the device the goal of the evolutionary process.

To state, evolvable hardware may seem merely the offspring of the marriage of computer hardware and evolutionary software. To the authors and their colleagues, however, it differs fundamentally from evolutionary computation. The definition of evolvable hardware hinges on whether or not electronic circuits play a fundamental role in the evolutionary process; the hardware is in the loop, so to speak, as opposed to the entire evolutionary process being run as a software simulation. These circuits may be off-the-shelf digital devices, such as field-programmable gate arrays (FPGAs) like Xilinx's Virtex II, or newly developed circuits, as we shall see, which employ reconfigurable circuits (reconfigurable logic) to create a new circuit.

Even more recently, a novel evolutionary algorithm was developed by two other researchers also seeking to evolve analog circuits, Jason Lehn and Silvano Colombo from the NASA Ames Research Center, in Moffett Field, Calif. Their approach is simpler in some respects than the one used by Koza and his colleagues [Fig. 1].

In all cases, the entire evolutionary process was carried out as a software simulation, with fitness of the candidate designs calculated by means of the Spice circuit simulator, the de facto standard for analog circuits. At no time did any hardware undergo an evolutionary change. Classified as evolutionary circuit design, this work is a subdomain of evolutionary computation. It is an important area of application that includes a multitude of real problems and promises exciting results.

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**Genetic Instructions**

transistor(N, ACTIVE_NODE, NEW_NODE, INPUT_NODE);
transistor(N, RAIS, ACTIVE_NODE, PREVIOUS_NODE);
resistor(const_to_ps(4.6108679e-04));
sensor(const_to_input(1.62843e-06));
transistor(N, NEW_NODE, ACTIVE_NODE, GROUND_NODE);
resistor(const_to_ps(9.39679e-04));
transistor(N, NEW_NODE, NEW_NODE, GROUND_NODE);
transistor(N, NEW_NODE, ACTIVE_NODE, PS_NODE);
resistor(N, NEW_NODE, ACTIVE_NODE, NEW_NODE);
resistor_move_to_output(1e-06);

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**Evolved Circuit**

1. This genetic code at top created the circuit below it. Conjoining up new circuits is merely a matter of editing the code lines and generating new values for the circuit elements. As the code is relatively simple, the rules for reproduction and mutation can also be simple.

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but even with construction of the evolved circuit that emerges from the simulation, it is not evolvable hardware.

For an application to qualify as evolvable hardware, the presence of real electronic circuits, rather than software simulation, is a must. This is not just a chronological attitude toward software on the part of hardware designers; using real hardware fundamentally changes the evolutionary process—and its results.

For one thing, there is no need to transfer the result of a simulation to hardware, whereas this step is a problem for several software-based efforts. Designing a car, for example, is far more impractical, as the actual hardware—instead of a simulation—during the evolutionary process makes the end result much predictable.

**EVOLUTION, OFF- AND ON-LINE**

To qualify as evolvable hardware, then, the design process must go beyond simulation and use real electronic circuits. There are two ways of doing this: off-line and on-line.

With off-line evolvable hardware, the circuit is merely a reconfigurable servos used for measuring fitness, while the evolutionary algorithm runs on a master computer.

In a simple off-line application within the field of evolutionary robotics, Adrian Thompson, of the University of Sussex, Brighton, England, evolved an onboard controller for a robot. [Fig. 2] The goal of

[2] Mr. Chips, the wheeled robot (far left) developed by Adrian Thompson at the University of Sussex, provides the platform on which to check out circuits for navigating a small area without bumping into walls. The control circuit is evolved on an off-line system and downloaded into Mr. Chips, thereby enabling researchers to check the viability of a design in a real environment quickly.

[3] The ideas of Hugo de Garis and his colleagues about implementing a cellular automata machine (CAM) have led to the construction of the CAM-Brain Machine (CBM) by start-up Genemity Inc. of Boulder, Colo.

Up to 64,000 modules can be placed in the CBM, resulting in billions of cells that can each be updated thousands of times a second, fast enough for real-time control of robots. The aim of the project is to build a billion-neuron artificial brain by 2001.
Self-improvement for ICs

"We have crossed a technological barrier beyond which we no longer need content ourselves with traditional approaches to engineering design..." wrote Eduardo Sanchez and Marco Tomassini in the proceedings of the first ever Conference on Evolvable Hardware, held in Lausanne, Switzerland.

What technological barrier did they mean? In part it was the need for a fundamental grasp of the theory and application of evolutionary computation—a need that had been met in the last few years. The other part was the lack of mealleable hardware, which had been overcome by progress in computer hardware, and especially in field-programmable gate arrays (FPGAs).

An FPGA is a large, fast integrated circuit that can be modified, or reconfigured, almost at any point by its end-user (see figure). Physically, it consists of arrays of logic cells linked by an infrastructure of interconnects and each using an array of transistors to realize some circuit function.

The device can be configured at any or all of three levels: the function of each logic cell, the interconnections between cells, and the cell inputs and outputs. All three levels are programmed with a string of bits that can be loaded from an external source repeatedly; hence the IC is reconfigurable.

A basic distinction created by the novel technology is one between programmable and configurable circuits. A programmable circuit iterates ceaselessly through a three-phase loop: an instruction is fetched from memory, decoded, and then passed to the execute phase. The process may call for several clock cycles, and is repeated for the next instruction, and the next, and so on.

A configurable circuit, on the other hand, can be regarded as having but a single, noniterative fetch phase. The so-called configuration string, fetched from memory, requires no interpretation and is used just as it is to set up the hardware for a given task. No further phases or iterations are needed. The ability to control the hardware in such a direct manner gives the user access to a far wider range of functions, but at the price of a more arduous design task.

Within the domain of configurable computing, two types of configuration strings can be distinguished: static and dynamic. A static string, which adapts the circuit to perform a certain function, is loaded once at the outset, thereafter changing not at all during execution of its task. Static applications are mainly aimed at attaining the classical goal in computing: improved performance, be it in terms of speed, resource utilization, or area usage.

Conversely, a dynamic configuration string is able to change during task execution. Dynamic systems adapt to and keep on functioning in various circumstances, forming an excellent substrate for implementing adaptive, evolvable systems. The behavior of an FPGA circuit changes every time a novel configuration string is downloaded into the configuration register. In a typical engineering application, the circuit is designed to behave in a fixed manner, in accordance with preordained specifications. Borrowing biological terminology, we could say that we are given the phenotype desired—the mature organism—and asked to find its genotype—the underlying genetic specification.

Engineers usually solve the phenotype-to-genotype problem by resorting to various analytical and empirical tools that have accumulated over the years; logic design is full of them (ECAD, for example). With evolvable hardware, the phenotypic behavior is given and evolution is used to find the underlying genotype.

---M.S. & E.M.A.R.

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The firefly machine was built by Moshe Sipper and his colleagues from the Swiss Federal Institute of Technology, Lausanne, Switzerland [Fig. 1]. They designed the circuit board to improve the way it performed a synchronized-oscillation task—similar to the way a swarm of fireflies will attempt to pulse their lights on and off in unison. It was an early proof of concept of the idea of online evolvable hardware.

More practically, several on-line chips for specific applications have been designed and fabricated by Teruyuki Higuchi and his colleagues at the Evolvable Systems Laboratory of the ElectroTechnical Laboratory in Tsukuba, Japan. They have built both digital and analog circuits aimed at commercial devices: an analog chip for cellular phones, a clock-tuning architecture for gigahertz systems, a neural-network chip capable of autonomous reconfiguration, and a data-compression chip for electrocardiographic printers.

Higuchi and his colleagues have also built a general-purpose chip for on-line evolvable hardware and used it to implement a controller for an artificial hand controlled by electric pulses from the nerves in the arm muscles [Fig. 5]. In normal conditions, a disabled person trains for over a month before being able to manipulate a prosthetic hand with ease. Reversing this scenario, Higuchi and his colleagues had the artificial hand adapt itself to the disabled person, instead of having the person adapt to the hand. The idea was that the on-line controller should accept signals from the nerves in the arm and map them to desired hand actions. Because those signals vary greatly between individuals, it is impossible to design such a circuit in advance. But with the evolvable-hardware controller, the hand usually requires less than 10 minutes to adapt to its owner through on-line training, in which the person repeats various hand movements—a notable improvement over the one month required when the owner is the one doing the adapting.

Off-line and on-line evolvable hardware each offer distinct advantages. The off-line approach allows the engineer to use all the computing power available in his laboratory and to employ sophisticated evolutionary algorithms to tackle the design problem at hand, while keeping actual hardware in the loop. The on-line approach holds out the possibility of setting loose an evolving device in its target environment, where it will adapt to perform its intended function. For instance, the hand-controller chip has
to be placed in a lightweight prosthesis band. Similarly, in an on-line robotic application (as opposed to the off-line one described above), the goal is to send the cumbersome workstation packing and let the robot remain with an evolvable chip in what passes for its belly.

Some form of on-line adaptation is, in fact, the only possibility where dynamic environments are concerned: a robot sent to explore the surface of Jupiter cannot be reprogrammed entirely in advance, and will therefore have to adapt on-line.

**FINDING THE UNKNOWN**

Up to this point, the "hand engineering" aspects of evolvable hardware have been the focus, namely applications within the existing "species" of analog and digital devices. Now the question is whether it is possible to generate new species, entirely novel designs, whose underlying structure and functionality are more than evolutionary — they are revolutionary.

Unconventional electronic design through artificial (as opposed to natural) evolution has been explored at the University of Sussex in Brighton, where Adrian Thompson, Paul Layzell, and Richard Zebulum evolved a number of analog digital circuits, including the aforementioned robot controller and a tone discriminator.

In these cases, evolution was unshackled by standard digital concerns. No spatial-structure constraints (such as limiting the number of recurrent connections) were placed on the evolving configurable device, an FPGA. Nor were there any impositions on modularity (such as insisting that two functions need to co-reside on the same module) or any dynamical constraints (such as the insistence on having a synchronizing check or handshaking between modules).

The evolved circuits resembled nothing that an engineer would design. Thompson, Layzell, and Zebulum concluded: "What initially seemed daring hypotheses are now either matter-of-fact, or within reach. From the vastness of design space, practically useful novel reconfigurations".

Elsewhere in Britain, an attempt was made to find not just novel circuits but novel circuit types. Julian Miller at the University of Birmingham and Peter Thomson of Napier University in Edinburgh are evolving arithmetic circuits, such as 2- and 8-bit binary multipliers using evol-
Researchers at the Electrotechnical Laboratory in Tsukuba, Japan, used evolvable hardware to develop a prototype artificial hand that adapts to a patient's unique arm-muscle activity. Typically, the adaptation is the other way round: people control the hand by learning to modify their muscle activity.

GROWTH OPPORTUNITIES

The third source of inspiration, ontogeny, is the one least studied to date by engineers. Ontogeny is the process by which multicellular organisms develop, through the successive divisions of a fertilized mother cell, known as the zygote.

Drawing inspiration from this fundamental natural process, a Swiss group has been developing the embryonic project. Among their number are Daniel Mange from the Swiss Federal Institute of Technology, Lausanne, and Pierre Marchal from the Centre Suisse d'Electronique et de Microélectronique in Neuchâtel.

Embryonic, for electronic electronics, aims at developing very large-scale ICs, capable of self-repair and self-replication. These two properties of natural organisms are attained in hardware by implementing in ICs certain features of natural ontogeny. The ability to self-repair enables an electronic "organism" to recover from minor faults, while the ability to self-replicate allows such an organism to recover from a major fault, by creating a novel, faultless clone. The Swiss group has built a number of prototypes to date, one of which is the BioWatch - a self-repairing watch [Fig. 6].

The clock-like BioWatch cannot break down. The circuitry that supports it is able to detect any flaws in its performance due to faults in its circuits and reconfigure the hardware to compensate.

[6]

TO PROBE FURTHER


The special Transactions issue of September 1999 (Vol. 3, no. 3) was entitled "From Biology to Hardware and Back." Edited by Moshe Sipper and Daniel Mange, it contained such articles as "Real-world applications of analog and digital evolvable hardware" by Tetsuya Higuchi, et al. (pp. 220-35), and "Explorations in design space: Unconventional electronics design through artificial evolution," by Adrian Thompson, Paul Layzell, and Ricardo S. Zebulum (pp. 167-98) and in "A circuit representation technique for automated circuit design" by Jason D. John and Silvano P. Colombano (pp. 205-19).


Evolution of Parallel Cellular Machines: The Cellular Programming Approach by Moshe Sipper (1997) is considered a classic text in this field. So, too, is Towards Evolvable Hardware, edited by Eduardo Sanchez and Marco Zombini (1996). Both books are published by Springer-Verlag, Heidelberg, Germany, as are the proceedings of the International Conference on Evolvable Systems.

For more information on the use of FPGAs in evolvable hardware, see "Static and Dynamic configurable systems" by Eduardo Sanchez, Moshe Sipper, Jacques-Olivier Haenri, Jean-Luc Beuchat, André Stawffer, and Andrés Pérez-Utrera, published in the IEEE Transactions on Computers, Vol. 48, no. 6, pp. 556-64.

As for the introductory quotation, it was taken from an article by anthropologist Melvin Konner, "A piece of your mind," in Science, July 1998, Vol. 281, pp. 652-54.

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