Stanford Ovshinsky and the Genesis of the Cognitive Computer

By Lillian Hoddeson, Peter Garrett, and Guy Wicker

Stanford Ovshinsky (1922–2012) was a prolific independent inventor who ended up with more than 400 patents.[1] Many of his inventions were motivated by his strong social concerns. His commitment to replacing fossil fuels, which began before 1960 and continued to the end of his life, resulted in important alternative energy technologies, including a system for mass-producing thin-film solar panels and the nickel metal hydride battery, still in use today. However, another dimension of his career now seems even more important: his contributions to areas of advanced information technology that are only now coming to fruition. The most remarkable of these, begun over 60 years ago, established the basis for creating a cognitive computer.

This month's history article traces and highlights Stanford Ovshinsky's contributions to advanced information technology that are only now coming to fruition.

I. BRAINS AND COMPUTERS

A computer that works like the human brain, whose operations are quite different from those of digital computers, has become a leading goal in current information research.[2] In conventional computers, logical processors and memory are separated, and binary switches are used to implement and connect them. With increasing processing speed, design complexity, and memory size, the demands of constantly transmitting signals between the processors and the memory have imposed limits on performance. In the brain, however, where memory and processing are not distinct, these limits do not apply. Instead, each of its neurons is electrochemically connected to about 10 000 others. While the brain's signals are transmitted more slowly than those of a computer (in tens of milliseconds instead of nanoseconds), with 10^{11} interconnected neurons, the brain's power far exceeds that of today's supercomputers for some applications. Even though computers may, in some respects, reach the brain's level of complexity, as long as their processors and memory remain separate, restrictions on data transmission will still limit their power. The research aimed at eliminating that separation has made progress in recent years, but it typically depends on using conventional computers to emulate faster designs for which some of the necessary components do not yet exist. While reports of this work stress its achievements and promise, they mostly fail to acknowledge the long history that has anticipated some of its advances. An important part of that

[1] For an account of Ovshinsky's life and work, see L. Hoddeson and P. Garrett, *The Man Who Saw Tomorrow: The Life and Inventions of Stanford R. Ovshinsky*. Cambridge, MA, USA: MIT Press, 2018. Unattributed quotations here are from interviews with Ovshinsky conducted between 2005 and 2012 by Lillian Hoddeson and presently held by her.

[2] For some recent work with affinities to Ovshinsky's, see: A. Pantazi, S. Wozniak, T. Tuma, and E. Eleftheriou, "All-memristive neuromorphic computing with level-tuned neurons," *Nanotechnology*, vol. 27, no. 35, 355205, 2016; T. Tuma, Angeliki Pantazi, M. Le Gallo, A. Sebastian, and E. Eleftheriou, "Stochastic phase-change neurons," *Nature Nanotechnol.*, vol. 11, 2016, pp. 693–699; N. K. Upadhyay, H. Jiang, Z. Wang, S. Asapu, Q. Xia, and J. Joshua Yang, "Emerging memory devices for neuromorphic computing," *Adv. Mater. Technol.* vol. 4, 1800589, 2019, pp. 589–602; S. Yu, "Neuro-inspired computing with emerging nonvolatile memories," *Proc. IEEE*, vol. 106, no. 2, Feb. 2018, pp. 260–285; D. Kuzum, R. G. D. Jeyasingh, B. Lee, and H.-S. P. Wong, "Nanoelectronic programmable synapses based on phase change materials for brain-inspired computing," *Nano Lett.*, vol. 12, no. 5, 2012, pp. 2179–2186; T. Moraitis, A. Sebastian, and E. Eleftheriou, "The role of short term plasticity in neuromorphic learning," *IEEE Nanotechnology,* vol. 12, no. 3, Sep. 2018, pp. 45–53; C. Ríos *et al.*, "In-memory computing on a photonic platform," *Science Advances,* vol. 5, no. 2, Feb. 2019, pp. 1–9.

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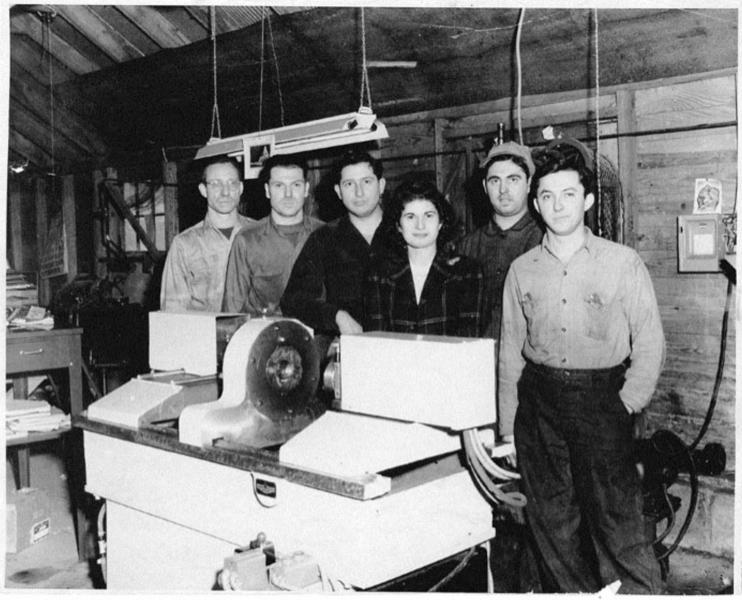

Fig. 1. ***Ovshinsky, standing third from the left with staff behind his Benjamin center drive lathe.***

history centers on Ovshinsky's unique career, which moved through areas far removed from those where information technology has usually developed.

II. FROM MACHINE TOOLS TO NERVE CELLS

Ovshinsky, whose formal education did not go beyond high school, began working in 1941 as a machinist and toolmaker in the shops and factories of Akron, OH, USA. He became an inventor by thinking hard about how to improve the current machine tools, and by 1946, he had created his first major invention, a high-speed automated lathe. Here, as in his later inventions, Ovshinsky worked like a scientist from basic principles. He recognized that it was unnecessary movement, whether mechanical play or chatter of the cutting tool, that slowed machining, and he designed his lathe to eliminate it. As a result, Ovshinsky's Benjamin center drive lathe could make cuts much faster and deeper than previously possible.

The radical innovations of Ovshinsky's lathe, like its rigid base and hydraulic chuck, initially met with skepticism from the traditionalists at the New Britain Machine Tool Company, to which he sold his small company in 1950, but when he demonstrated that it could operate about ten times faster than their machines, they embraced his design and built over 200 of the lathes that were first used for machining steel artillery shells for the Korean War.

Ovshinsky's first invention was a great success, and several of its features have become common in machine tools, but he was already looking ahead. His efforts to automate more of his lathe's operations soon led to the automation of other machines, pursued as he moved to Detroit and began working in the thriving automobile industry. Again, he looked for basic principles, which he found in Norbert Wiener's recent books on cybernetics.[3] Applying cybernetic principles, Ovshinsky created control devices using sensors and feedback in several automotive inventions, including an electrical automatic transmission and electrical power steering, but in designing intelligent machines, he also sought a more general understanding of intelligence.

The most radical feature of cybernetics is the way it uses the same concepts to analyze both animate intelligence and inanimate intelligence: the full title of Wiener's influential 1948 book is *Cybernetics; or Control and Communication in the Animal and the Machine.* This approach led Ovshinsky to an extended investigation of nerve cells; he not only read deeply in the current neurological literature but also contributed to it himself in a series of papers and participated in experimental research on motor control at the School of Medicine, Wayne State University. Even though he had no credentials beyond a high school diploma, Ovshinsky received this research opportunity on the strength of his 1955 paper on "The Nerve Impulse," which contained the seeds of his later work on artificial intelligence.[4] Here, Ovshinsky proposed an analogy between the nervous system and a biased electrical circuit,

[3]N. Weiner, *Cybernetics; or Control and Communication in the Animal and the Machine*. Cambridge, MA, USA: MIT Press, 1948; *The Human Use of Human Beings*. New York, NY, USA: Houghton Mifflin, 1950.

[4]The paper was not published, but Ovshinsky sent a copy to Ernest Gardner, the Chair of anatomy at Wayne State. It can be found in the Ovshinsky papers in the Bentley Historical Library at the University of Michigan, Ann Arbor, MI, USA.

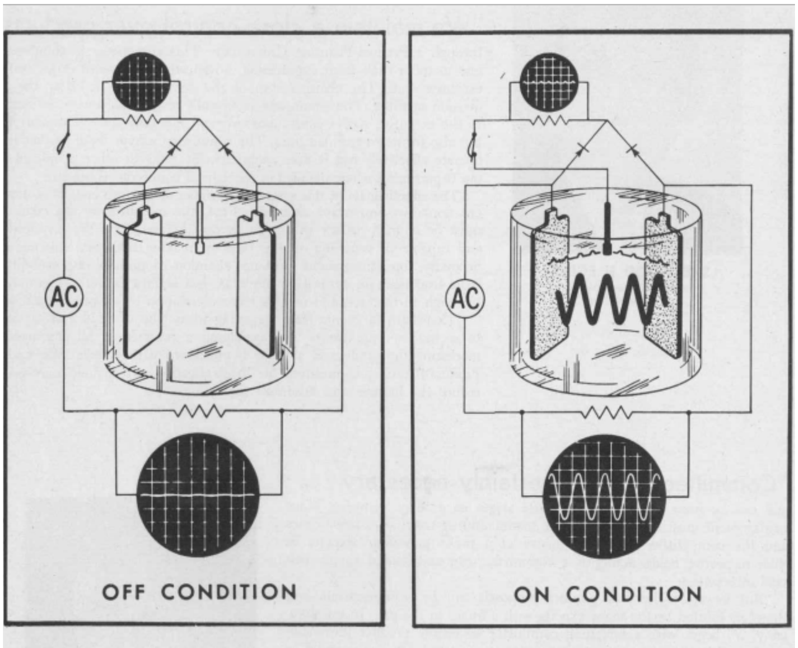

Fig. 2. ***Operation of the Ovitron switch.***

which led him to question conceptions of the nerve impulse as "a strictly on-and-off event," a case of "all or nothing." It is instead, he argued, modulated: numerous excitations accumulate until they reach a threshold and the neuron fires, a process for which "there are many electromechanical analogies."

This conception of switching as a cumulative rather than binary operation is the basis of the cognitive devices Ovshinsky would create nearly 50 years later. More immediately, it led in 1958 to his creating an electrochemical switch that he called his "nerve cell analogy." Built with his younger brother Herb, the device resembled an electrolytic battery, with tantalum electrodes immersed in a hydrochloric acid electrolyte containing a small amount of zinc. When an ac voltage was applied, no current flowed because of a thin insulating oxide film on the electrodes, but when an additional low positive dc voltage was introduced by a third, nonreactive (palladium or platinum) electrode, the device switched on. Reversing the dc polarity switched it off again.

Ovshinsky thought of the electrolyte as being like the fluids surrounding neurons, and, more importantly, of the oxide coating on the tantalum electrodes as being like the cell membrane, a semipermeable barrier that allows transmission when cumulative stimulation reaches a certain threshold. The Ovitron, as Ovshinsky named his switch, was fast, robust, and efficient, switching in 8.3 ms and yielding a large power gain: the dc current of only a few milliamperes at about 3 V could control an ac current of as much as 20 A at about 100 V. Because, unlike the transistor, it could handle such heavy ac loads and because it worked differently from previous switches, it attracted a great deal of attention.[5] Today, we can recognize that over 60 years ago, Ovshinsky was working to create an artificial neuron, the same project that engages current research in cognitive computing.

III. FROM THE OVITRON TO PHASE-CHANGE MEMORY

Ovshinsky, however, did not continue working on the Ovitron because the terms of a lawsuit settlement prevented him from developing switches using the same design and materials. He had to find new ones, and that led him to his most important discovery. After an extensive search through the periodic table for materials to replace the Ovitron's oxide layers, he settled on the chalcogens, the elements grouped under oxygen in column 16 (then 6). Changing to a solid-state design, he experimented with thin films of chalcogenide alloys, combining tellurium with neighboring elements such as arsenic and antimony.

In 1961, Ovshinsky's experiments resulted in a breakthrough. Chalcogenides are amorphous (noncrystalline) materials, which normally have high resistance, but he found that as he increased the voltage applied to his material, it reached a threshold where the thin chalcogenide film suddenly became highly conductive.[6] Observing a remarkable "cross" pattern on his oscilloscope, Ovshinsky

[5]The Ovitron was the subject of several articles in trade journals. See "The electrochemical relay: A remarkable new switching form," *Control Eng.*, July 1959, pp. 121–124; "How liquid-state switch controls A-C," *Electronics*, Aug. 14, 1959, pp. 76–80; "Nerve-cell studies lead to new static component," *Electronic News*, Jul. 23, 1959, p. 10.

[6]For a detailed reconstruction of Ovshinsky's path to this discovery, see L. Hoddeson and P. Garrett, "The discovery of Ovshinsky switching and phase-change memory," *Physics Today*, Jun., 2018, pp. 44–51.

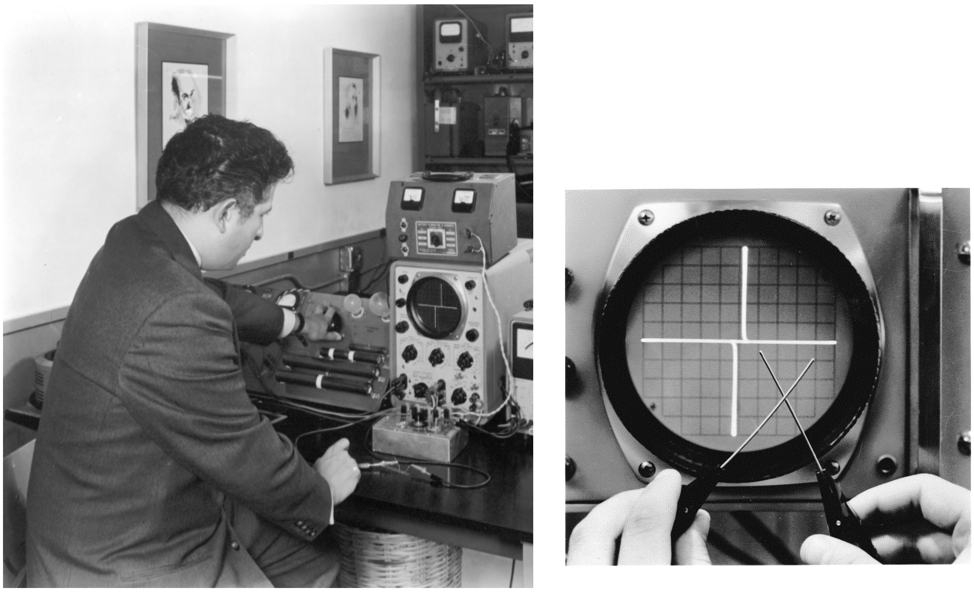

Fig. 3. ***Ovshinsky observing the characteristic "cross" pattern of his switching effect on an oscilloscope.***

immediately recognized that he was seeing something new, something that the current crystalline-based teachings of solid-state physics could not explain.[7] Unlike a transistor or diode, the behavior of Ovshinsky's threshold switch was reversible and bipolar, and these features led to many innovations. The discovery opened up the new field of amorphous and disordered materials that Ovshinsky would go on to exploit in all his most important subsequent inventions.

Further experimentation in the early 1960s with what is now known as the Ovshinsky effect yielded an important variation on the threshold switch, a device that, once switched on, remained in the low resistance state until a second pulse returned it to high resistance. This became the basis of phase-change memory, in which successive pulses change the material from amorphous to crystalline and back. As Ovshinsky later explained, his goal had always been "to reproduce the brain cells with their synapses in solid-state matter"; with the invention of the Ovonic threshold switch and the Ovonic memory switch, he had placed that goal within reach.[8] All the current advances in neuromorphic devices that depend on chalcogenide rather than silicon materials stem from this pioneering work Ovshinsky did many decades ago.

Although the importance of Ovshinsky's switching discoveries has now become clear, they initially provoked intense resistance. Solid-state (now condensed matter) physics was then concerned almost entirely with the study of crystals, whose regular, periodic atomic structure made them amenable to quantum-mechanical calculations. Furthermore, crystals had become the basis of the growing semiconductor industry that took off with the invention of the transistor in 1947. Making semiconductor devices from amorphous and disordered materials was not considered possible and when in 1968 Ovshinsky reported he had done that the announcement drew incredulous and hostile responses from both academic and industrial researchers.

Part of this hostility was provoked by the way Ovshinsky's discovery was blazoned on the front page of the *New York Times,* which seemed to mark him as a publicity-seeking self-promoter rather than a respectable scientist.[9] On the same day, however, the prestigious journal *Physical Review Letters* published his report of his discovery, giving it a claim to scientific credibility.[10] That publication, however, enraged some established researchers even more. The resistance clearly arose not only from the way Ovshinsky's claims contradicted current scientific doctrines but also because he was an unknown outsider with no academic position or credentials. The view of Ovshinsky

[7]The oscilloscope, in a circuit with the switch and an ac source, is configured as a curve tracer, the X-axis showing voltage and the Y-axis showing current, whose values are indicated by a bright spot. As the voltage alternates 60 times a second, the spot moves, but the voltage changes so rapidly that the eye sees the spot's path as a linear trace. Amorphous material normally has such a high resistance that the current remains very small and the trace looks horizontal. As the voltage increases and reaches either a positive or negative threshold value, the switch suddenly becomes so highly conducting that the spot jumps almost vertically up or down, producing the "cross" pattern repeatedly traced over billions of ac cycles.

[8]As with the Ovitron, Ovshinsky named his new materials for himself. "Ovonic," a portmanteau combination of "Ovshinsky" and "electronic," became the description for several more of his inventions. As an independent inventor, he needed to promote his own work, but the term irritated even some of his admirers.

[9]W. K. Stevens, "Glassy electronic device may surpass transistor," *New York Times,* Nov. 11, 1968, p. 1, 42.

[10]S. R. Ovshinsky, "Reversible electrical switching phenomena in disordered structures," *Phys. Rev. Lett.,* vol. 21, no. 20, pp. 1450–1453, Nov. 11, 1969.

Fig. 4. ***ECD's two-sided medallion.***

as an outsider may partly explain why even today, when work based on his discoveries is playing an increasing role in information technology, he has not received appropriate credit.

IV. ENERGY AND INFORMATION

Up to this point in the mid-1960s, Ovshinsky had mainly worked alone, but now licensing revenues from his switching inventions enabled him to establish his own research and development company, Energy Conversion Devices (ECD), where a growing cohort of trained scientists helped to develop and commercialize his discoveries. As the company's name signaled, a leading goal was the creation of energy technologies that offered alternatives to fossil fuels, which Ovshinsky recognized as the source of both environmental and political threats. It was the collaborative work of ECD scientists under Ovshinsky's direction that led to the roll-to-roll machine that produced thin-film solar panels "by the mile," making them newly affordable, and to the nickel metal hydride battery that powered GM's ill-fated electric car, the EV1, and that is still used in hybrids such as the Toyota Prius. These, like many other ECD technologies such as flat-panel displays or a hydrogen-powered car, depended on the amorphous and disordered materials that Ovshinsky had pioneered in developing.

However, for tracing the genealogy of the cognitive computer, the most important ECD programs were its information technologies based on phase-change memory. An early success was the optical memory, the basis of rewritable CDs and DVDs, where phase changes in the chalcogenide material are triggered by a laser rather than an electrical pulse. Development of the electrical memory also continued, as D. R. Nelson reported in 1970. His article titled "Ovonic device applications" described for the first time memory arrays in which Ovonic memory switches were combined with Ovonic threshold switches, a design that later became the basis for important advances in memory technology.[11]

[11] D. R. Nelson, "Ovonic device applications," *J. Non-Crystalline Solids,* vol. 2, pp. 528–539, Jan. 1970. This is the basis for the recent 3D Xpoint, discussed below.

Much more work was needed, however, before chalcogenide switches could compete with the silicon devices on which the growing computer industry was based. An important step came from research on increasing the speed and reducing the energy requirements for the optical memory. Collaboration with Matsushita followed by independent research at ECD yielded the "225" alloy, consisting of germanium, antimony, and tellurium ($Ge_2Sb_2Te_5$). With a repeatable switching time of 50 ns or less, optical memories based on it were around 1000 times faster than those using earlier alloy and required less energy. Ovshinsky believed the 225 alloy would work even faster in an electrical memory. Despite the skepticism of most of his advisors, experiments proved him right: devices using the alloy could be set with just a 10-ns pulse. By 1993, ECD had also developed a consistent production process that showed the potential for making a competitive electrical memory.

Developing electrical phase-change memory at this point required more support, which came first from collaboration with Micron and then in 1999 from a joint venture with Micron's former Chief Scientist, Tyler Lowrey. The new company, called Ovonyx, for Ovonic Unified Memory, licensed the technology to most of the major chip manufacturers, while it continued to pursue research and development. Their phase-change memory was superior to the dominant flash memory: roughly, 100 times faster with a much longer cycle life and greater efficiency. Flash memory also eventually faced strict limits as it scaled down, while phase-change memory, with its lower power requirements, actually functions better as it scales down. Despite these advantages, the lower cost of flash memory and the computer industry's massive commitment to it kept phase change from realizing its potential. After Ovshinsky was forced out of ECD in 2007, Ovonyx continued to develop phase-change memory for two years, but then stopped, and after ECD's bankruptcy filing in 2012, the patents were sold to Micron.

In 2015, however, Intel and Micron surprised the computer industry by announcing their 3D Xpoint memory chip: "a major breakthrough in memory process technology and the first new memory category since the introduction of NAND flash in 1989."[12] At first, the composition of the device was not disclosed, but six months later Intel and Micron confirmed what ECD and Ovonyx veterans had already deduced, that this revolutionary new device was essentially the same as the one they had created for Ovshinsky in 1989, combining Ovonic threshold and memory switches, invented nearly thirty years earlier, in a 3D array. As an Intel–Micron executive proclaimed, "Chalcogenide material and an Ovonyx switch are magic parts of this technology with the original work starting back in the 1960s."[13] This statement acknowledges the origins of the device in general terms but fails to mention either Ovshinsky or the way ECD had created this "magic" technology long before.

V. OVONIC COGNITIVE COMPUTING

While Ovonyx was working in the early 2000s to commercialize electrical phase-change memory, Ovshinsky and a small team of ECD researchers were developing an even more advanced information technology based on chalcogenide switching. Offering a way to realize Ovshinsky's aim "to reproduce the brain cells with their synapses in solid-state matter," this program was the culmination of work that began with his efforts in the 1950s to probe the nature of human and machine intelligence. It included his paper on the nerve impulse, and his Ovitron, threshold, and memory switches; all this work fed into Ovshinsky's attempt to build a cognitive computer.

[12]"Intel and Micron produce breakthrough memory technology," *Intel News Release,* Jul. 28, 2015 https://newsroom.intel.com/news-releases.

[13]"3D Xpoint steps into the light," *EE Times,* Jan. 14, 2016, http://www.eetimes.com/document.asp?doc_id=1328682.

Fig. 5. *Stanford Ovshinsky, with his favorite resource, the Periodic Table.*

The possibility of achieving this emerged in 2002 when the physicist Boil Pashmakov found that the energy required to set one version of the phase-change memory could be composed of a number of lower energy pulses. That allowed the device to accumulate information until it reached the threshold for switching from amorphous to crystalline, just as Ovshinsky had described the cumulative rather than binary switching of the neuron. Many operations, from basic arithmetic to factoring and encryption, could now be performed within a single nanoscale device, vastly increasing processing speed; joining many of these neurosynaptic devices opened the way to massive parallel processing. By eliminating the separation between memory and processing, the Ovonic cognitive device offered the basis for a computer that could emulate the brain.

The creation of this cumulative phase-change memory was not only the culmination of Ovshinsky's decades of work on neuromorphic devices but also an expression of his long-held belief that information and energy are complementary. He called them "the twin pillars of the global economy," conceived them as two sides of the same coin and commemorated the 20th anniversary of ECD in 1980 with an actual coin whose faces bore images of the sun and the brain. To many physicists, including several who worked with Ovshinsky, this way of thinking made no sense; they could understand it only as a version of the relationship between information and entropy, a central concept in both thermodynamics and information theory. But while Ovshinsky thought in terms of fundamental principles, they were typically not the abstract formalisms used by trained physicists. He instead produced his idiosyncratic intuitions through analogies and a highly developed visual imagination. He understood the complementarity of energy and information in concrete physical terms rather than theoretical abstractions, and he found the confirmation for his view in the cognitive device, where incremental pulses of energy were stored. As he put it, "You are adding energy, adding energy, adding energy, adding energy, and you are making little crystallized regions. When these regions connect to form a percolation path, then it fires like a nerve cell."[14]

To incorporate the cognitive device in a circuit, Ovshinsky and Pashmakov created a three-terminal threshold switch, in which a signal applied to the third terminal, analogous to the third terminal of a transistor, could change and control the threshold voltages at which the cognitive device would fire. Invented in 2006, the three-terminal device was designed to work in a circuit with the cognitive device as part of a chain in which the output of one affects the input of the next. Ovshinsky filed several patents on his cognitive devices and published some

[14]Ovshinsky interview by Lillian Hoddeson. For a discussion of percolation in amorphous solids, see R. Zallen, *The Physics of Amorphous Solids*. New York, NY, USA: Wiley, 1983, pp. 135–204.

accounts of the technology.[15] But funding for development was limited in the years after 2002, when Ovshinsky's control at ECD was diminishing, and further research was completely terminated in 2007, when he was forced to retire.

After leaving ECD, in early 2008, he formed a new company, Ovshinsky Innovation, where a small, dedicated group of former ECD employees continued his work with amorphous and disordered materials. Ovshinsky wanted to resume the development of his cognitive computer along with other discontinued research programs, but he decided to devote his limited resources to work on a process for greatly increasing the production of thin-film solar panels, which he felt would have the most immediate impact. The program made some progress, but all the company's work ended with Ovshinsky's death in November 2012.

Ovshinsky's death, however, hardly ended research in chalcogenide switching materials. As the example of the 3D Xpoint shows, those efforts have instead intensified. The demonstrated higher density and performance of this device and the limitations of silicon metal–oxide–semiconductor technology are driving research into new alternatives. Meanwhile, Ovshinsky's project has been revived by former ECD employees, whose company, Ovonic Cognitive Computer, retains a license to the relevant ECD patents.[16]

The increasing efforts of such research programs give hope that the goal of cognitive computing, conceived long ago by Ovshinsky's visionary imagination and based on his breakthrough discoveries, may soon be realized. ■

[15]For example, S. R. Ovshinsky and B. Pashmakov, "Innovation providing new multiple functions in phase-change materials to achieve cognitive computing," *Mater. Rese. Soc. Symp. Proc.*, vol. 203, pp. 49–60, 2004.

[16]G. Wicker and B. Pashmakov, "Potential application of time dependent threshold switching in neuromorphic computing," *Non-Volatile Memory Technol. Symp.*, Aachen, Germany, vol. 17, Sep. 1, 2017, pp. 66–67. See also www.ovoniccognitivecomputer.com. In addition, Intel, Micron, and IBM Zurich all now tout this technology as the key to the next generation of truly cognitive computers.

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This article was sponsored by L. Dennis Shapiro. L. Dennis Shapiro is an IEEE Life Fellow and retired Chairman and past CEO of Lifeline Systems, Inc., now a part of Philips Electronics. He is a collector of historical manuscripts, including letters and documents signed by the early developers of electricity and radio communications. For information on supporting future Scanning the Past articles, please contact Stan Retif of the IEEE Foundation at s.retif@ieee.org.

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Peter Garrett is currently a Professor of English Emeritus and the former Director of the Unit for Criticism and Interpretive Theory, University of Illinois at Urbana–Champaign, Champaign, IL, USA. He is the author of studies of narrative form and mode in 19th- and 20th-century British and American fiction, including *Scene and Symbol from George Eliot to Joyce, The Victorian Multiplot Novel,*and *Gothic Reflections: Narrative Force in Nineteenth-Century Fiction*. *The Man Who Saw Tomorrow*is his first venture in the history of technology.

Guy Wicker is CEO of Ovshinsky Innovation, Pontiac, MI, USA. He worked with Ovshinsky between 1985 and 2012 on chalcogenide switching devices and in 1996 took his Ph.D. at Wayne State University, Detroit, MI, USA, for modeling the behavior and showing the scalability of these devices. He is presently implementing next-generation computers with threshold, memory, and optical switches, and continues to pursue work on the Ovonic cognitive computer.