Skyrmionic Technology for Atomic-Scale and Neuromorphic Computing

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1. Introduction

I was invited to write this article to help commemorate the 40th anniversary of *Computer Report*, the flagship publication of Informatics Society of Iran. So, I thought looking forward to where computer hardware technology could go four decades hence might be an interesting exercise. Mr. Dariush Abedi, Dr. Ghassem Jaberipur, and I recently completed an article that reviews technologies for atomic-scale computing and their affinity with majority logic, as candidates for super-dense, ultra-low-power realizations of arithmetic and other building-block computations [1]. Some such technologies are already in use, though not yet economical, while others are being studied with respect to efficient realizability and use.

Here, I focus on an exciting new atomic-scale technology, based on the particle-like skyrmion (skir'-mian), that goes further, because, like memristor [2], it combines storage and processing functions. In doing so, the technology potentially alleviates the "von Neumann bottleneck" [3], referring to the negative impact of the relatively low bandwidth between memory and processing subsystems (compared with the intrinsic memory bandwidth and achievable processing rate) that limits computation speed when data items must be fetched from memory, processed, and the results sent back to memory.

2. What Are Skyrmions?

While, strictly speaking, skyrmions do not represent new technology, their applications to memory and processing functions are new [4]. The idea of skyrmion dates back to the 1960s, when theoretical physicist Tony Skyrme, in whose honor the technology was later named, considered the particle-like elements for describing the behaviors of protons and neutrons [5], but was ultimately unsuccessful in this endeavor. Fast-forward to five decades later, when scientists realized that skyrmions could be created within magnetic materials, quite densely and reliably.

A magnetic skyrmion is the smallest possible perturbation to a uniform magnet, that is, a point-like region of reversed magnetization, surrounded by a whirling twist of spins, as seen in Fig. 1 [6]. A few nanometers in size, skyrmions are classified as quasi-particles: They do not exist in the absence of a magnetic state and their emergent electrodynamics is not simply described by Maxwell's equations. Skyrmions can be created, destroyed, and moved around, and they can interact with each other. Their long-term stability (non-volatility) makes them particularly useful as storage devices. According to MIT researchers [7], current speed disadvantages of skyrmions can be mitigated by using alternate materials, to render them competitive for high-speed computation.

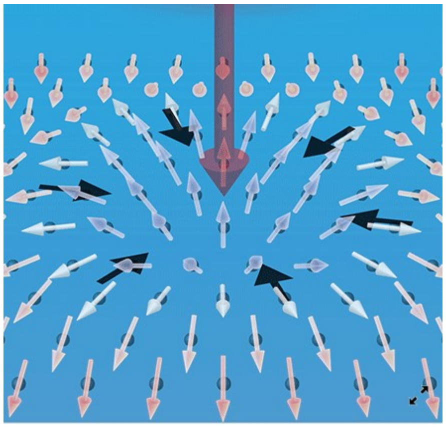

Fig. 1. A point-like region of reversed magnetism (here, upward) in a uniform magnet, a skyrmion's core is surrounded by an axially symmetric twist that returns the spin texture to the background direction (here, down) [6].

Practical use of skyrmionic technology require ironing out manufacturing problems and refining the read/write processes. It is estimated that a decade or more will be needed to resolve these problems. However, there is broad agreement that orders-of-magnitude improvements in speed and energy efficiency offered by the successful deployment of skyrmions are real and achievable.

3. Neuromorphic Computing

Attempts to mimic the computational processes of the brain, in order to benefit from their flexibility and extreme energy efficiency, have a long history [8]. Currently, computing devices are capable of simulating the behavior of only a small portion of the simplest animal brains. Thus, neuromorphic computing [9], that lumps together the study of neuron-like computational elements and mechanisms holds great promise.

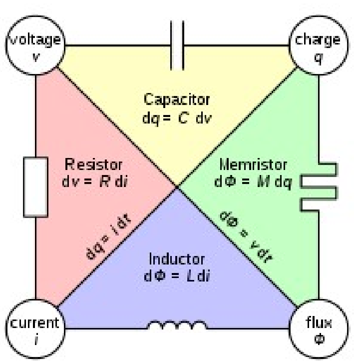

Fig. 2. Memristor, whose existence was hypothesized in 1971 based on conceptual symmetries of circuit elements, was demonstrated practically in 2007 [Image from Wikipedia].

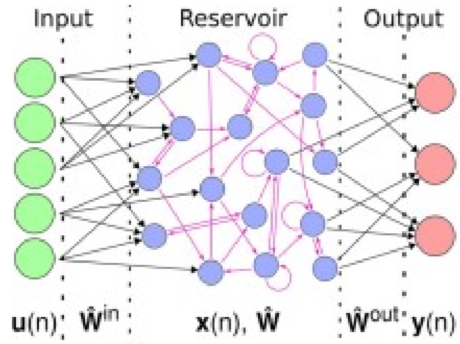

Fig. 3. A neural network consisting of input nodes (left), output nodes (right), and reservoir nodes (middle). I/O nodes have unidirectional connections, whereas reservoir nodes may be bidirectionally connected and have loops [10].

An intense competition is on to realize neuromorphic systems with various researchers' favorite technologies. Memristor (short for memory resistor), the fourth fundamental passive circuit element that complements resistor, capacitor, and inductor (Fig. 2), has already exhibited immense potential in this regard [2]. Skyrmions are also among prime candidates for helping realize this computational paradigm in the near future.

One scheme, being considered for putting skyrmions to good use, is reservoir computing [10], where the applicable recursive neural nets consist of input and output layers, with unidirectional connections to a collection of internal or reservoir nodes, themselves bidirectionally connected, potentially forming both single-node and multi-node loops (Fig. 3). Neural networks similar to the one in Fig. 3 are commonly used to classify similar input signals by producing identical outputs. Reservoir computing allows us to perform such functions quickly and with very low training-time overhead.

4. Looking to the Future

Scientists working on the technology hope that Skyrmions will replace all kinds of memory in our computers with dense, non-volatile storage that would make the notion of booting up a computer obsolete. Skyrmions can also combine information storage and processing functions via their interaction capability. Such a combination of storage and processing functions will lead to efficient schemes for realizing brain-like computing structures.

We note in passing that skyrmions are different from nano-scale bar magnets [11], another atomic-scale magnetic technology under consideration for super-compact, ultra-low-power computing devices [1]. In fact, after ceding the limelight to silicon-based technologies for decades, magnetic technologies are back in several forms, in view of both their desirable non-volatility property and advances in miniaturizing them.

I am enthusiastically following promising developments in atomic-scale computing technologies, which are attracting strong interest throughout the computing community, now that Moore's-Law scaling and other exponential improvement trends are approaching their ends. By the time *Computer Report* celebrates its 50th birthday, there should be good news on large-scale application of skyrmions and other atomic-scale technologies for storage and computing. Skyrmions realized in thin film structures are particularly promising for practical applications, as they can be readily shrunk to nanoscale dimensions [12].

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