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Non-Boolean Computing with Spintronic Devices

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Non-Boolean Computing with Spintronic Devices

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Abstract

In addition to the electron's charge, Spintronics deals with the electron's spin and magnetic moment for computation or data storage. Certainly, an extremely promising application of spintronic devices is data-storage; the remanence makes the memory non-volatile and instant-on. Moreover, these devices are thermally stable making them suitable for extreme-temperature operations.

In this monograph, we leverage spintronic devices for information processing and do not cover data-storage. We explore three non-Boolean computational framework: (1) Energy minimization based optimizer, which we recently published in Nature Nanotechnology [23], (2) Coupled Oscillatory framework [47] and (3) Neuromorphic learning framework. In Energy minimization framework, we harness the innate physical properties of nanomagnets to directly solve a class of energy minimization problems. Due to the fact that the Hamiltonian of a system of coupled nanomagnets is quadratic, a wide class of quadratic energy minimization can be solved much more quickly by the relaxation of a grid of nanomagnets than by a conventional Boolean processor. Another property that researchers have harnessed is achieving radio-frequency ferromagnetic resonance, which can be harnessed in a system of nano-oscillators to provide solution to dynamical systems. This property is also utilized in neuromorphic frameworks.

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Introduction

National Strategic Computing Initiative (NSCI), released by President Obama in July 2015, issues an executive order which outlines a few compelling objectives; the one that resonates most with this monograph is "Establishing, over the next 15 years, a viable path forward for future HPC systems even after the limits of current semiconductor technology are reached (the "post-Moore's Law era")." Indeed, in ITRS roadmap, a specific thrust is provided to "More than Moore era" [164] that embraces novel beyond-CMOS state variables and non-Von Neumann architectures.

In the decade of 2000, active research paradigm was to search for suitable alternative technologies that utilized charge transfer as the primary mode of computing (Figure 1.1). A few examples are Carbon Nanotube [189, 171], Graphene FET [229, 230], Tunnel FET [107, 53], Resonant tunneling diodes [148], Spin FET [176], Piezo [224] and NEMS [68]. However, there are other non-charge-based state variables like magnetization [96].

Memory technologies have seen an unprecedented growth. While 3D FLASH is the benchmark for non-volatile memories, many potential breakthroughs have happened through PCM [63], FeRAM [12],

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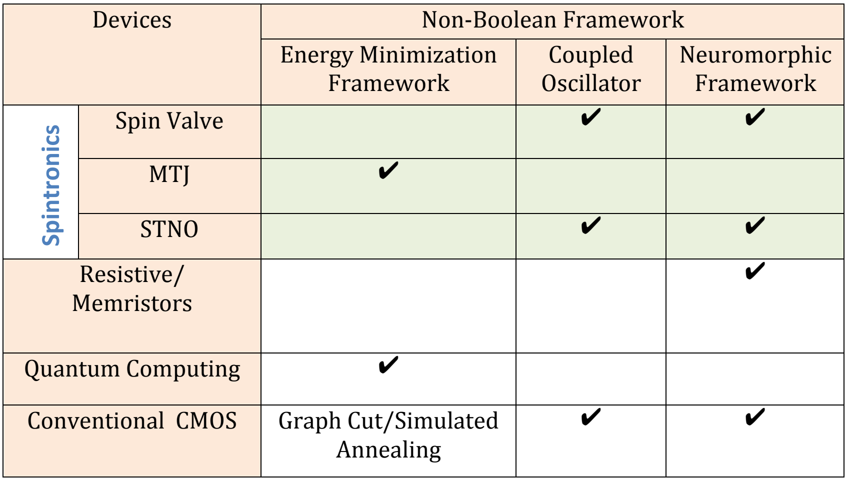

Devices		Non-Boolean Framework		
		Energy Minimization Framework	Coupled Oscillator	Neuromorphic Framework
Spintronics	Spin Valve		✔	✔
	MTJ	✔		
	STNO		✔	✔
Resistive/ Memristors				✔
Quantum Computing		✔		
Conventional CMOS		Graph Cut/Simulated Annealing	✔	✔

Figure 1.1: Emerging Devices and non-Boolean Frameworks

Spin-transfer-torque (STT)-MRAM [124, 83, 37]) and spintronic memories (Magnetoresistive Random Access Memory (MRAM) [58]. Since spintronic devices are the basis of MRAM and STT-MRAM, we focus on magnetization as the state variable in most parts of this monograph.

Unlike the conventional electronics, the core principle of spintronic devices leverages both spin and charge properties of electrons, rather than exploiting only the charge property. Spin property of electrons faced significant ignorance in conventional logic and information processing. Earlier, spin was only exploited for magnetic recording in a macroscopic way [38], where the magnetization of ferromagnet is used. The microscopic manipulation of the spin for controlling electron transport in a device became possible after the discovery of "Giant Magnetoresistance (GMR)" [15, 24] in 1988. Subsequently, the development of spintronic devices triggered research in a broad range of application domains, such as highly sensitive magnetic-field sensors [155], magnetic read heads [120], and nonvolatile magnetic memory applications [203]. High density, radiation hardness, and long data retention make MRAM an excellent choice for data storage and main memory in applications under unfavorable conditions.

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In a parallel endeavor, researchers have been mesmerized by the computation that occurs in nature and human brain. The energy efficiency clearly has significant supremacy over conventional Boolean processing for a multitude of complex tasks. While we do not have a clear understanding how the brain actually works, many hypotheses have emerged for bio-mimetic computing. In this monograph, we explore three directions: the first one with threshold logic based implementation of point-neural systems. While the research is still at early-stage perceptron model with discussion only on feed-forward networks, it is an important computing platform. Second, we showcase computation based on coupled oscillators. Computation based on coupled oscillator has been implemented for associative computing. This framework of computing follows Kuramato's model of phase synchronization which is observed in chem-bio systems. It is imperative in these models that elements which are associated with each other will achieve physical ground state when phases are synchronized. Finally, we will focus on an energy minimization Ising framework for optimization which is NP-hard. Many emerging technology platforms have employed these Ising models namely quantum annealing /citedwave1,dawave2, DNA [197]. Spintronics have a unique advantage of room temperature operations and interface with conventional I/O. Please note that the third framework is synonymous with the dynamical system of Hopfield neural networks [79]. Unlike Kuramato's framework which uses complex computing elements, Hopfield network models optimize binary elements.

The spintronics research has already established various flavors of alternate non Von-Neumann problem mapping like neuromorphic [157, 85, 134], and non-Boolean computing with oscillators [47, 48]. In general, coupled oscillators have shown to solve associative processes [122, 122, 167, 152]. Recently, pairwise coupling was experimentally demonstrated in [188]. Application-specific algorithms have been proposed for signal processing [49, 67, 65, 66] for a while. Another direction that has been popular is the cellular neural network (CNN) computing model [36, 35, 136, 156, 45, 62, 200, 129, 141]. Quantum-dot (QD) arrays have been explored [118, 117, 93] for low-level image processing applications. DWAVE's [8, 56] recent work uses quantum

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annealing to solve optimization problems at ultra-low temperature. In this manuscript, we focus on three basic paradigms.

In *threshold logic based Perceptron neural framework*, discussed in chapter 3, STNO are proposed for the neuron model while synapses are modeled by memristive and another crossbar architecture [184]. Two STNO are employed to create the neuron model. One of the STNO will be acting as reference and the other one processes the threshold logic output arriving from synapses. The output of the neuron will be dependent on the locking mechanism between the two STNOs. In some cases, an RF current source replaces the reference STNO to reduce the overhead. We have also discussed domain wall nanowire and lateral spin valve in the implementation of synapse and neuron assembly. Honestly, a comprehensive demonstration is crucial with back-propagation and batch training, which is currently not highlighted yet [13].

In *coupled oscillator framework*, discussed in chapter 4, energy transfer happens between a system of oscillators, and the entire system stabilizes in a new state (solving problems). Researchers are working on the oscillator systems that can process matching operations in parallel, and can provide a robust pattern matching which can be utilized in Associative Memory and ultra-fast search applications. We categorize spin-torque nano-oscillators (STNO) into three categories: (1) magnetically coupled with closely spaced neighboring spin torque oscillators, (2) electrically coupled spin torque oscillators, and (3) magneto-electrically coupled STNOs. While experimentally demonstrated, it appears that magnetic coupling is relatively harder to scale as geometric constraints are imposed. Most STNO utilize electrical coupling. While we visit the phase shift key technique, most of the STNO work relies on frequency shift key. Simulation results in effectively identifying patterns [91, 46]. Studies also suggests that frequencies are better optimized through a system of STNO over phase [46].

In *energy minimization framework*, discussed in chapter 5, the computational theme is mapping the quadratic energy minimization problem spaces into a set of interacting magnets. This way the energy relationship between the problem variables is proportional to that of the dipolar coupling energies between the corresponding magnets.

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The optimization is actually accomplished by the relaxation physics of the magnets themselves, and solutions can be read-out in parallel. In essence, given a specific instance of the problem, we will arrive at a specific magnetic layout, the relaxed state of which will be the solution to the original problem. In this monograph, we specifically discuss the quadratic optimization framework for various magnetic geometries and the rationale for a new state variable S which indicates if the magnetic nanodisk is in vortex state or not. We use the fact that the nanomagnetic disks in a critical dimension settle into two different magnetization ground states: a vortex state when weakly coupled, or a single domain state when strongly coupled. We also describe a mathematical model where both vortex and single domain magnets can both be expressed and we detail a magnetic Hamiltonian. We explain the visualization technique that is used to create a magnetic layout where pairwise energy between the magnetic cells, matches the same pairwise energies between the quadratic option problem variable (perceptual grouping problem in our particular case). We fabricated multiple magnetic layouts for the same areal image. Once the layouts are created by E-beam lithography and E-beam evaporation systems, we characterize them by Scanning Electron microscope and magnetic force microscope. The entire system is driven to the hard axis (perpendicular to the magnetic plane) by an externally applied magnetic field and the magnetic states are then observed through the microscope. We compare the system with IBM ILOG CPLEX optimization and show that this method is on an average is 1528 times faster than CPLEX with 4 neighbor sparse affinity matrices and is 468 times faster than CPLEX with 8 neighbor sparse affinity matrices.

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