Quantum-Materials for Energy Efficient Neuromorphic- Computing (Q-MEEN-C)
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Lead Institution: University of California, San Diego
Class: 2018 – 2022

Mission Statement: *To lay down the quantum-materials-based foundation for the development of an energy-efficient, fault-tolerant computer that is inspired and works like the brain ("neuromorphic").*

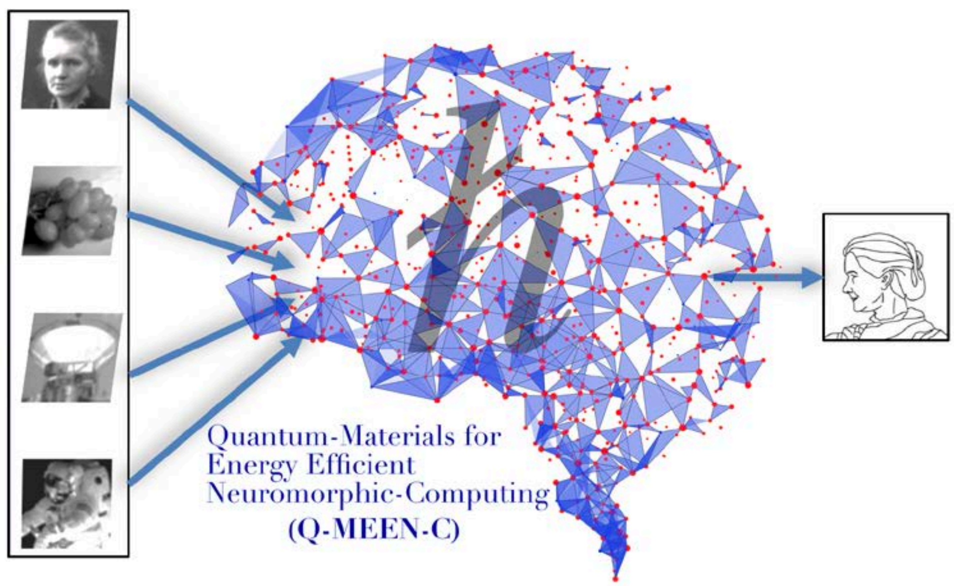

Fig. 1: Q-MEEN-C will develop the next-generation energy-efficient quantum-materials-based platforms which will be the basis of neuromorphic computing. In this example of neuromorphic computing, the image of a famous scientist is readily distilled from multiple disparate, complex inputs.

Energy-efficient neuromorphic computing offers a potentially disruptive technological capability to process complex inputs and produce elegantly simple, useful outputs as illustrated in Fig. 1. The breakaway from the conventional technology Turing-von Neumann paradigm requires the development of new types of bio-inspired ("neuromorphic") devices with functionalities like artificial synapses, neurons, axons, and dendrites that can be used to construct machines with artificial intelligence capabilities. We aim to address these critical issues on two different platforms based on *Charge*- and *Spin*-related phenomena in quantum materials.

Technical Implementation: The *Charge*-based approach relies mainly on nanostructured quantum materials, which exhibit spectacular, unexpected changes in their electrical properties when subject to temperature, electric, and magnetic fields, strains, and light. Essential components of neuromorphic information processors will include artificial neurons, synapses, axons, and dendrites to mimic biological entities for transmission and processing of signals. These types of components will be realized in simple transition metal oxides or complex strongly correlated oxides, which exhibit metal-insulator transitions (MIT). In this fashion, we will aim to emulate typical neuronal activities, such as leaky-integrate-fire behavior, symmetric and asymmetric synaptic plasticity, and self-sustained oscillations. Eventually, several of these will be incorporated into complex circuits and architecture. Specific goals of these part of the EFRC are: 1) Identifying material platforms that can be controlled by non-thermal means such as electric fields, currents, strain, and light, 2) understanding ionic transport under highly non-equilibrium conditions, and 3) determining the ultimate limitations of MIT in these materials platforms.

The *Spin*-based approach relies on the implementation of neurons and synapses using heterostructured spin-torque oscillators, based on quantum-materials phenomena such as spin-orbit scattering. Neurons are emulated with magnetic oscillators, and the coupling between them mimics synapses. A charge current sent through these oscillators is converted into a spin current that drives magnetization precession of nanoscale structures in a sustained and coherent way at room temperature. The underlying magnetization dynamics are highly non-linear, and tunable in phase, amplitude and frequency. Therefore, spintronic nano-oscillators can strongly modify their dynamics in response to small incoming signals resulting in outstanding phase locking and mutual synchronization properties. This is key for neural networks, where neurons should respond to external inputs, but also to signals coming from other neurons through synapses. Specific goals of these part of the EFRC are: 1) Design materials for efficient operation of oscillators, 2) Develop approaches that are best suited for reconfigurable coupling between oscillators and 3) Engineer large-scale oscillator networks that generate complex dynamics.

The scientific thrusts will be interconnected with cross-cutting methods spanning novel materials design, state-of-the-art characterization, modern theory and computation (Fig. 2). A key strength of Q-MEEN-C combines these approaches to understand and harness 'designer' quantum material-based heterostructures with useful behavior for developing artificial, energy-efficient neurons, synapses, and axons. This will be achieved through multimodal imaging, spectroscopy, and diffraction techniques, coordinating with sophisticated modeling and simulation tools.

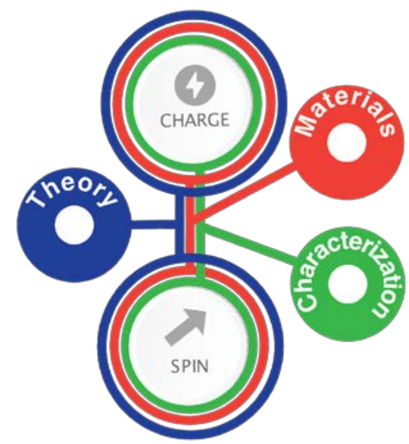

Fig. 2: Integration of our scientific thrusts with cross-cutting tools.

Byproducts: The research on quantum materials to be performed will produce as "byproducts" important basic research results relevant to electromigration, materials-property prediction, novel tools, and new materials and functionalities. From the technical point of view, the coordinated application of a large battery of synthesis, characterization, and theoretical tools makes this a comprehensive center that could not be successful without such an interdisciplinary, collaborative effort.

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