

ECE 492-057 & ECE 592-113

Physical AI with brain-inspired electronics

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Objective or Description: Over millions of years of evolution nature has found efficient solutions to given problems and specific needs. Although not always providing optimal solutions, nature has definitely equipped living organisms with the ability to survive, evolve and thrive in a dynamic, unpredictable, antagonistic and at times hostile environment. Nature has incorporated efficiency via cognition, intelligence, robustness and redundancy in any manifestation of living organisms. This efficiency is clearly observable in the behavior of living organisms and is a major source of inspiration for the development of contemporary electronics. It is estimated that a classical computer capable of performing $\sim 10^{15}$ - 10^{17} floating point operations per second would be needed to match the computational power of the human brain. Such a supercomputer would consume several megawatts of power, which is vastly higher than the brain's 20-watt consumption. Instead of relying on traditional computing systems to execute neural algorithms, biological processes can be directly implemented on brain-inspired electronics, which are designed to emulate biological functions in an energy efficient and multi-modal manner (see Figure).

Even beyond engineering metrics, the brain is different than conventional electronics: this sophisticated mass of cells operates in a “wetware” (immersed into salt water) and uses as carriers of information ions, neurotransmitters and biomolecules. The brain continues to be a major source of inspiration for researchers worldwide, as it still holds many mysteries to be uncovered. Starting from biological cells/signaling and moving to contemporary applications, this course is a journey to the field of brain-inspired electronics, with an ultimate goal to integrate diverse forms of intelligence “everywhere”.

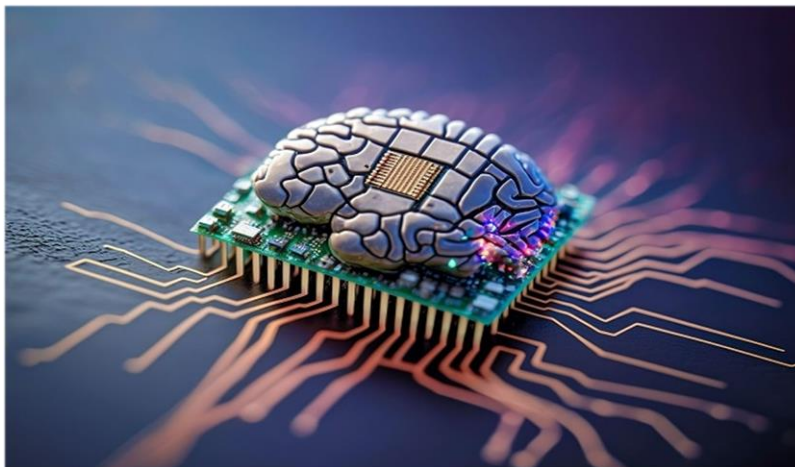


Figure. An artist's representation of physical AI with brain-inspired electronics, in which, the biological/artificial borderline is blurred.

Prerequisites: Interest in microelectronic devices, unconventional electronics, computing, biophysics, neuroscience

Textbook: Multiple sources

Topics: History of electronics & computing, limitations, elements of neuroscience (ions, cells, neurons, synapses, higher-order phenomena), artificial synapses & neurons, contemporary applications (physical ANNs with memory arrays, on-chip processing & classification, logic & decision making, adaptive & evolvable electronics, sensorimotor learning in robotics, neuromorphic bio-interfaces, biocomputing)

Grading: Active participation (40%), project #1 (20%), project #2 (20%), project #3 (20%)

Week (#)	Chapter	Part	Content (lecture #)
1	Part A: Fundamentals	A1. Introduction	History of computing: scaling laws, current limitations (energy, efficiency, fault-tolerance, complexity) Why neuromorphic?: motivation, SoA, examples of commercialization...
2-3		A2. Elements of neuroscience	Building blocks of biological networks: Cells, membranes, ions & ionic channels, neurotransmitters Synapses: structure & function, types of synapses, plasticity, synaptogenesis, synaptic scaling, memory Neurons & information theory, structure & function, action potential, excitability, firing modes, types of neurons, dendrites & computation, neural oscillations, physiology & pathology, neural computation & metabolic efficiency Higher-order phenomena in biological networks (homeostasis, neural trajectories, spatiotemporal computing, global-local coupling, neural synchronization, brain-wide functional connectivity)
4-6		A3. Brain-inspired electronics: reverse engineering biology	Artificial synapses 1: analogue memory technology Artificial synapses 2: operation principles (Silicon, FeRAM, metal-oxide, RRAM, PCM, MRAM, 2D, organic...) Artificial neurons 1: oscillatory electronics, event-based signaling Artificial neurons 2: models (integrate & fire, leaky integrate & fire, Hodgkin-Huxley...), characterization Emulating higher-order phenomena in biological networks (homeostasis, spatiotemporal computing, synchronization, functional connectivity)
7		Recap & discussion	- Recap & discussion of Part A, project definition <i>Project#1</i> assignment (journal club-like)
8	Project week (Project#2)		<i>Project#2</i> assignment (exercise) <i>Project#2</i> presentation/submission
9-11	Part B: Applications	B1. From artificial synapses to physical ANNs	ANNs: basic function, training, inference, ANNs with memory cross-bar arrays, Kirchoff's laws & matrix operations Other networks & paradigms, reservoir computing, in materio computing, oscillatory computing, Hopfield networks
		B2. Neuromorphic computing and processing	On-chip computing & classification: edge computing, near-sensor/in-sensor computing - Reconfigurable & adaptive circuits, logic & decision making, evolvable electronics
		B3. Neuromorphic biointerfacing & robotics	Neuromorphic biointerfacing, biohybrids, biocomputing - Intelligent agents, neurorobotics, sensorimotor control & learning
12		Recap & discussion	- Recap & discussion of Part B <i>Project#3</i> assignment (exercise)
13	Project week (Project#3)		<i>Project#3</i> preparation (students only) <i>Project#3</i> presentation/submission