

RealTime-Biology Electrogenetics Brain-Computer Interface Vision

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At the intersection of biology and technology, a new frontier is emerging: a new class of **Brain-Computer Interfaces**, or **BCIs** for short. Synthetic, genetically encoded materials that endow biology and silicon with the capability to seamlessly integrate with each other.

So far, silicon microelectrode arrays and more recently **optogenetics** modules have served as the bio-interfaces to interact with neurons but suffered from low biocompatibility and low spatial resolution, imagine watching an 8K movie with a 16-pixel TV. What if we could build something that would allow silicon to interface with neurons at the same complexity and resolution neurons interface with each other?

Electrogenetics aims to do just that. Electrogenetics is the field of harnessing, repurposing, and de novo design of electron-conductive, genetically encoded materials that enable neurons to communicate with the language of silicon, electrons, and silicon to grow protein fibers to intimately contact neurons, forming the **biology's upper-limit BCIs**. This is a BCI that allows neurons to interact with computers the same way they interact among themselves.

A **key enabling technology**, **protein design**, only recently evolved to allow creating complex systems. Today, protein materials can be designed at atomic precision to feature functions such as electron conduction. They can be designed to grow from specific neuronal membrane sites, self-heal, and withstand environmental conditions that are considered extreme for living structures, such as stability beyond 100°C. They can be encoded to be built within the neurons or added externally, making them an ideal technology platform to connect living neurons and devices.



In nature, bacteria living deep in ocean sediments, deprived of oxygen, evolved an alternative respiration that instead releases electrons which are then shuttled across the membrane through special protein electron ports and across millimeter distances through extruded electron-conductive protein fibers. These **two** key processes: 1. the biochemistry involved in electron release, and 2. long-range cross-barrier electron transfer, repurposed or designed de novo to operate within and between neurons and silicon hardware, are the fundamentals of **Electrogenetics-based BCIs**.

How would this work in practice? Action potentials, the electrical signals of the nervous system, travel down the axons. Through a programmable, designed cascade, these ionic signals are transduced into an electron release event, shuttled across the neuron membrane through a special electron port, and to the silicon through self-assembled protein electron wires.

These dynamic protein wires readily enable **bidirectional communication**. In a similar fashion, a silicon-axon port bridge facilitates the reading event, a silicon-dendrite port facilitates the writing event. This allows the silicon to determine the initiation or the blocking of specific action potentials while continuously reading incoming signals.

This bidirectional single-axon, single-dendrite-resolution signal flow is then used to construct a sophisticated, detailed map of the body and brain, providing a real-time view of our internal state. This enables early identification of distant injury or pathology through anomalous signal patterns, paving the way for **timely intervention**.

Additionally, for the first time, silicon gains direct, molecular-scale access to the architecture of biological intelligence, not as an observer, but as a participant. Continuous thought processes, encoded in the temporal dynamics of neural circuits, become accessible to silicon in a way that external electrodes cannot achieve. This is not simply interfacing with the brain; it is the foundation for **hybrid computing**: systems where biological and silicon computation are not separate domains connected by a bottleneck, but a unified substrate. The implications extend from understanding how cognition emerges to building computational platforms that leverage the efficiency, adaptability, and parallelism of biological neural networks alongside the speed, scale, and precision of silicon.