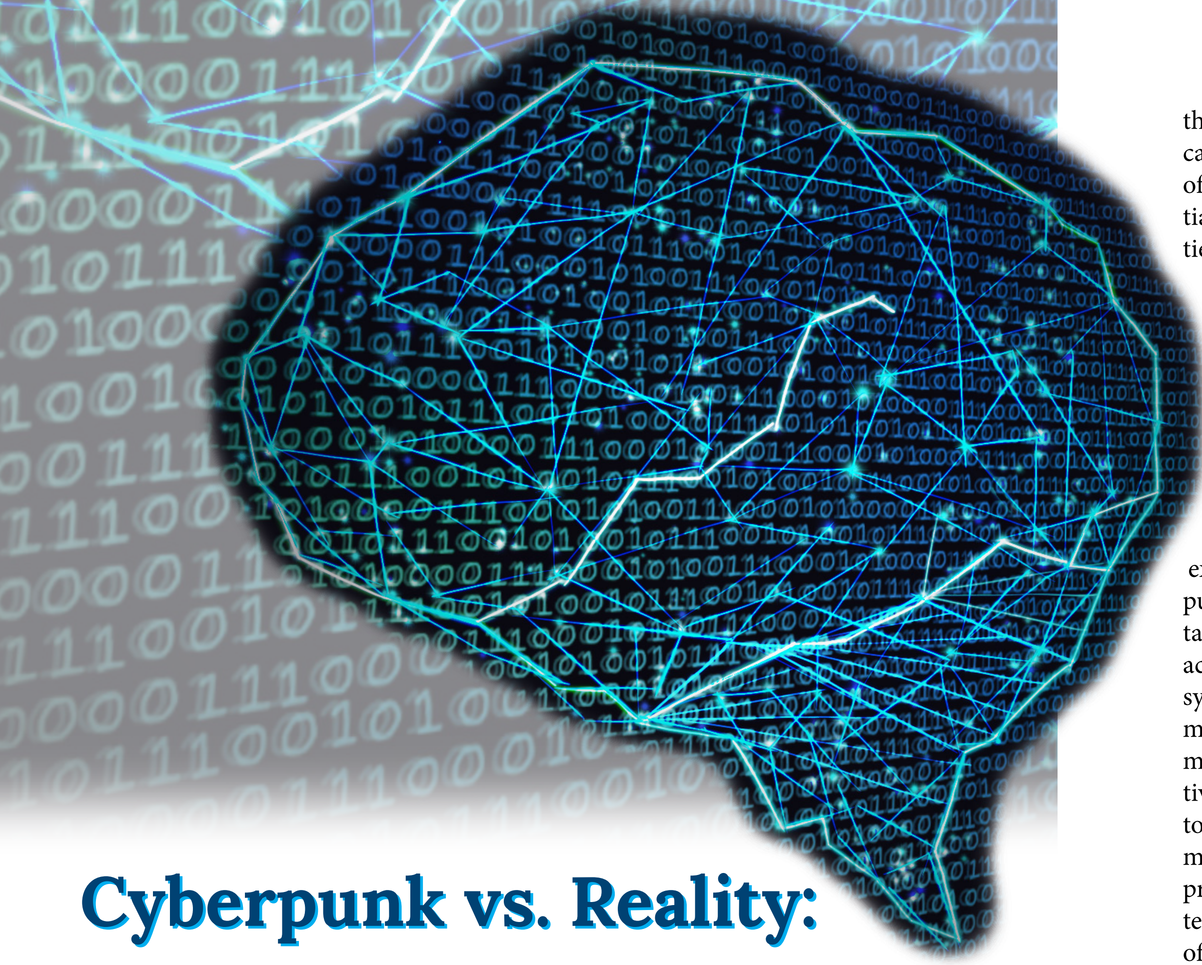


Cyberpunk vs. Reality:

Brain-Machine Interface

by Samme Xie
art by Audrey Ruan

Imagine the world of the Matrix, where reality comes from inserting wires in one's brain and connecting with a supercomputer to create an illusion of the real world. Or imagine Professor X, wearing a brain-enhancing device to manipulate people's minds. Even though each depiction seems far from reality, the technology behind them has been developing for several decades and still demonstrates enormous potential. This technology, called Brain-Machine Interface (BMI), is a system that translates brain signals into commands that can be relayed to output devices that carry out desired actions [1]. Motor circuitry consists of connections between central and peripheral neurons and the muscles required for the desired movement. BMIs can mimic this circuitry by creating an interface between specific neuronal signals and prosthetic devices to perform intended actions. With unique approach of replacing peripheral nerves and muscles with prosthetic devices using signals from the central nervous system, BMIs can be used to interpret the intent of paralyzed patients, restore partial or even full limb mobility in patients suffering from motor deficits, study cognitive representation and functions in the cortex, and even enhance the natural central nervous system (CNS) output [2,3].

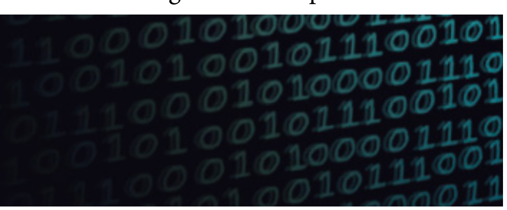
Designing an electric circuit that controls artificial limbs with our mind requires a thorough understanding of how our brain exerts motor control. The brain output pathways follow two fundamental principles: one is that combined activities from the central nervous system produce control over spinal motoneurons that further activate muscles. The second is that the adaptive plasticity of neurons gives rise to our capacity to acquire and refine motor skills [4]. The initiation and production of behaviors involve interactions among various regions of the brain, rendering accurate motoneuron output to coordinate activities in all related brain areas. This intricate network, however, is subject to disruption following spinal cord lesions or development of neurodegenerative diseases that lead to progressive paralysis. BMIs, in this case, may be used to replace the original pathway or assist neurohabilitation. Most BMIs, compared to CNS output pathways, do not incorporate spinal motoneuron activations that lead to muscle contractions but instead output cortical signals (e.g., the sensorimotor cortex) directly to prosthetic limbs to produce desired movements. Other BMI applications are used to bypass the areas causing paralysis and reanimate paralyzed muscles via electrical stimulation without the use of external devices [5].

> ***"...BMIs can be used to interpret the intent of paralyzed patients..."***

The major components to reconstruct BMIs routes include signal acquisition, signal processing, and device output [6]. The first step, signal acquisition, relies on recording electrodes to acquire, amplify, and digitize detected neural activities using either recordings of electroencephalograms (EEGs) or implanted chips in the brain tissue. The EEG-based BMIs decipher the subject's voluntary intentions by measuring the combined electrical activity of massive neuronal populations [7]. EEG signals are complex spatiotemporal signals with high temporal resolution but poor spatial resolution. Although EEG signals can relay spontaneously, they depend on the coverage and the quantity of electrodes on the scalp for better resolution [8]. EEG also has limited capacity for multiple communication channels and thus is incapable of controlling large prosthetic limbs that require a high degree of flexibility. Despite its shortcomings, this non-invasive method enables the control of computer cursors for paralyzed or locked-in patients to communicate with the outer world [9]. To overcome some of the limitations of EEG, small microelectrodes can be inserted into the brain to yield higher-resolution signals. By implanting microelectrodes into the cortex, we can extract firing patterns for individual neurons and limited populations of neurons to construct real-time mathematical models that generate motor control commands and subsequently reproduce voluntary motor behaviors [10]. Although intracortical electrode recordings from single cells support precise control of a robotic arm, those implants may fail to function reliably in clinical settings due to the tissue's acute and chronic response to them [11].

Once digitized signals are acquired through EEG or intracortical recordings, the second step of constructing BMIs is signal processing which involves feature extraction and a translation algorithm [13]. Feature extraction procedures analyze brain events to distinguish signal characteristics pertinent to a patient's intentions and represent them in a form suitable for further translation. Such procedures involve measuring neuronal firing amplitude or discriminating brainwave patterns for mental state recognition, which attempt to represent users' motives [14]. The resulting features are then passed to the next phase: feature translation. The translation algorithm converts

the independent variables (signal features) into dependent variables (device control demands). An effective algorithm is dynamic and adaptive. It adapts to spontaneous variations (e.g. hormonal level) and learns changes in the user's signal features to ensure that the user's possible range of feature values covers the full range of device control. Moreover, the algorithm accommodates and engages the adaptive capacities of the brain, in other words, improving future BMI operations with knowledge from prior BMI operations. Ideally, the brain will modify signal features to increase their correlation with the user's intent over time [13]. Ultimately, the commands extracted from the feature translation algorithm then operate on an external prosthetic device, providing functions such as cursor control, robotic arm operation, and so forth.

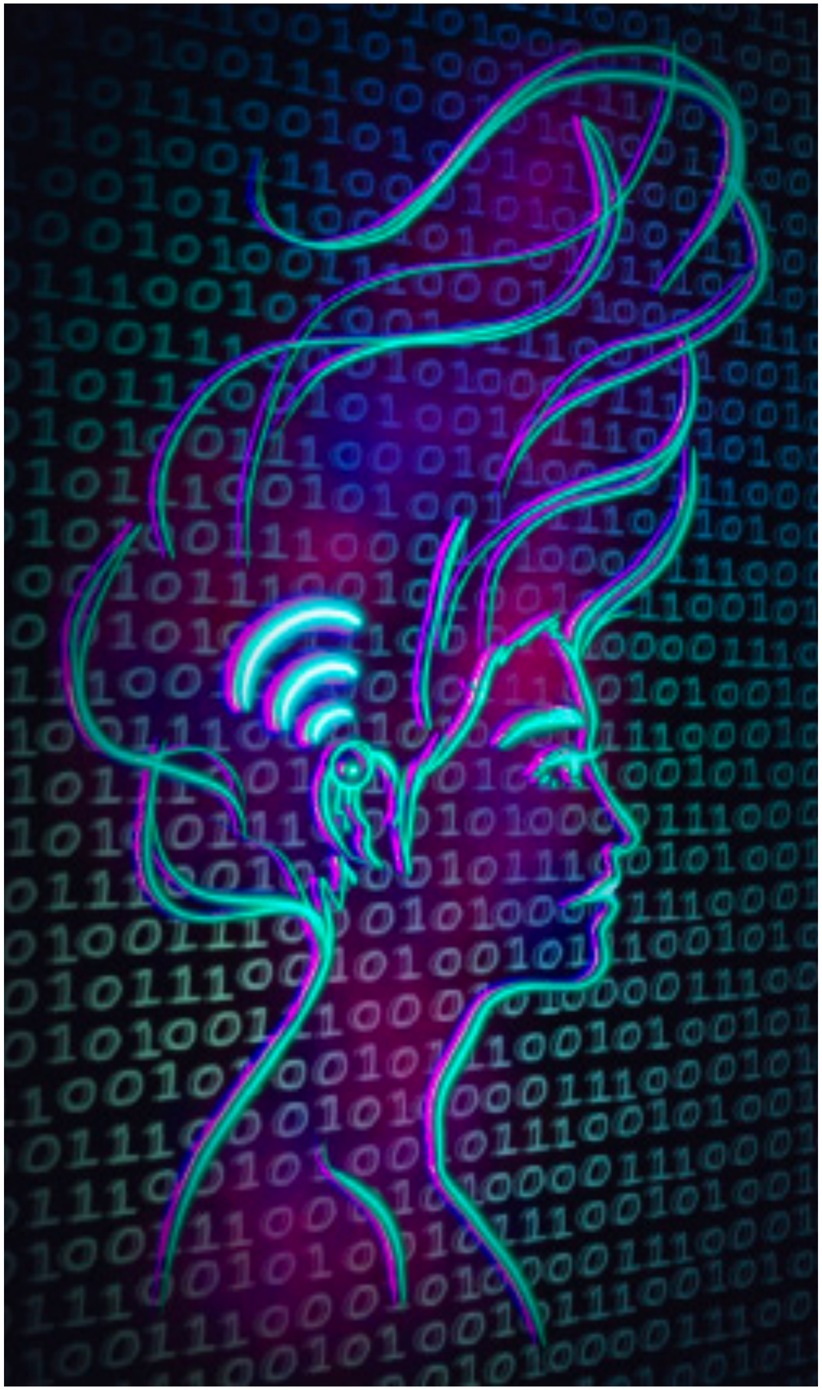


Constructing a BMI pathway is made possible by many milestone research studies and the availability of cutting-edge techniques in interdisciplinary fields. The earliest systematic human BMI investigations can be traced back to the 1970s when Vidal attempted to evaluate the feasibility of using electrical brain signals to carry information in person-computer communication [14]. Further research suggested that by training subjects to control certain sensorimotor rhythms (e.g., mu and beta rhythms) recorded by EEG, they could move a cursor on a computer screen [15]. Ever since the first experimental demonstration with rats in 1999–which showed that signals derived from motor cortex neurons can be used for predicting trajectories of movements and real-time device control—basic research in BMIs has progressed at a stunning pace [2]. Several groups have successfully established a mathematical connection between neuronal firings and movements as well as reproduced those movements with robotic arms. For example, one research group showed that cortical neuron activity in monkeys can be used to control a mechanized arm for self-feeding [16].

In addition to basic research, there are emerging clinical studies that aim to restore functions in handicapped individuals. A study in 2012 demonstrated direct control of a robotic arm to perform multidimensional movements with signals decoded from a small population of motor cortex neurons in tetraplegia patients [17]. A more recent study de signed a BMI that decodes the handwriting movements from the motor cortex and translates them to text in real-time, enabling quadriplegic patients to input 115 English characters per minute [18]. Neuralink, a neurotechnology company founded by Elon Musk, strives to develop implantable BMI to restore both sensory and motor function in individuals with neurological disorders.

"...established a mathematical connection between neuronal firings and movements..."

The Neuralink device is proposing to implant microscale threads containing thousands of electrodes into the brain tissue to detect and translate neural signals into machine-readable algorithms. The vision of Neurolink on neurorehabilitation and BMI proposes a foreseeable future that merges the human brain with AI [19].



Promising as it sounds, the effective and large-scale application of BMIs still has many problems that call for resolution. One challenge is to design effective signal processing approaches that decode the complexity of the human cortex, an organ composed of millions of neurons that transmit information in a nonlinear manner. Additionally, we are still unclear about how a neuron contributes to larger-scale cognitive events that produce behaviors. All these uncertainties impede the development of multiscale signal processing techniques that capture broad representation from neuronal assemblies [20]. Another challenge that hinders extensive applications of BMI is determining how to establish stable chronic neural interfacing and minimize tissue response for independent home use. Current technology requires surgically placing the electrodes close to the neuron and fixing their location for the highest quality recordings. However, variability is inevitable because implants can shift over time along with neural tissue and degrade from immune response. Thus, it is not only critical to find material compatible with brain tissues, but also important to establish a stable, endurable interface through developing more precise implanting procedures [21].

As we blur the boundary between the machine and the human body, ethical issues arise with this emerging technology. For instance, some are concerned about the potential threat that BMI applications impose on au-

tonomy and privacy [22]. Because the essence of BMI technology is to extract information from the brain to manipulate machines, it is reasonable to suspect that some information could be transferred beyond the person's control. An example of violating privacy would be to utilize brain waves reflected by EEG as a valuable information source for advertising and commercial purposes to analyze consumer behavior. Other concerns arise from the merging of he brain with machines. As neuroscience advances and microelectronic devices increasingly optimize, our notion of personhood becomes challenged with more widespread BMI applications [23]. What is the boundary of BMI application? Is it right to use BMI to enhance the functions of healthy individuals? How do we ensure that the risks of invasive implants are minimalized during research? These are all pressing questions to ask if we want to realize BMI technology's full potential and avoid the pitfalls of hasty application.