Thought experiments

How brains and machines can be made to work together

Brain-computer interfaces sound like the stuff of science fiction. Andrew Palmer sorts the reality from the hype

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IN THE gleaming facilities of the Wyss Centre for Bio and Neuroengineering in Geneva, a lab technician takes a well plate out of an incubator. Each well contains a tiny piece of brain tissue derived from human stem cells and sitting on top of an array of electrodes. A screen displays what the electrodes are picking up: the characteristic peak-and-trough wave forms of firing neurons.

To see these signals emanating from disembodied tissue is weird. The firing of a neuron is the basic building block of intelligence. Aggregated and combined, such "action potentials" retrieve every memory, guide every movement and marshal every thought. As you read this sentence, neurons are firing all over your brain: to make sense of the shapes of the letters on the page; to turn those shapes into phonemes and those phonemes into words; and to confer meaning on those words.

This symphony of signals is bewilderingly complex. There are as many as 85bn neurons in an adult human brain, and a typical neuron has 10,000 connections to other such cells. The job of mapping these connections is still in its early stages. But as the brain gives up its secrets, remarkable possibilities have opened up: of decoding neural activity and using that code to control external devices.

A channel of communication of this sort requires a brain-computer interface (BCI). Such things are already in use. Since 2004, 13 paralysed people have been implanted with a system called BrainGate, first developed at Brown University (a handful of others have been given a similar device). An array of small electrodes, called a Utah array, is implanted into the motor cortex, a strip of the brain that governs movement. These electrodes detect the neurons that fire when someone intends to move his hands and arms. These signals are sent through wires that poke out of the person's skull to a decoder, where they are translated into a variety of outputs, from moving a cursor to controlling a limb.

The system has allowed a woman paralysed by a stroke to use a robotic arm to take her first sip of coffee without help from a caregiver. It has also been used by a paralysed person to type at a rate of eight words a minute. It has even reanimated useless human limbs. In a study led by Bob Kirsch of Case Western Reserve University, published in the *Lancet* this year, BrainGate was deployed artificially to stimulate muscles in the arms of William Kochevar, who was paralysed in a cycling accident. As a result, he was able to feed himself for the first time in eight years.

Interactions between brains and machines have changed lives in other ways, too. The opening ceremony of the football World Cup in Brazil in 2014 featured a paraplegic man who used a mind-controlled robotic exoskeleton to kick a ball. A recent study by Ujwal Chaudhary of the University of Tübingen and four co-authors relied on a technique called functional near-infrared spectroscopy (fNIRS), which beams infrared light into the brain, to put yes/no questions to four locked-in patients who had been completely immobilised by Lou Gehrig's disease; the patients' mental responses showed up as identifiable patterns of blood oxygenation.

Neural activity can be stimulated as well as recorded. Cochlear implants convert sound into electrical signals and send them into the brain. Deep-brain stimulation uses electrical pulses, delivered via implanted electrodes, to help control Parkinson's disease. The technique has also been used to treat other movement disorders and mental-health conditions. NeuroPace, a Silicon Valley firm, monitors brain activity for signs of imminent epileptic seizures and delivers electrical stimulation to stop them.

It is easy to see how brain-computer interfaces could be applied to other sensory inputs and outputs. Researchers at the University of California, Berkeley, have deconstructed electrical activity in the temporal lobe when someone is listening to conversation; these patterns can be used to predict what word someone has heard. The brain also produces similar signals when someone imagines hearing spoken words, which may open the door to a speech-processing device for people with conditions such as aphasia (the inability to understand or produce speech).

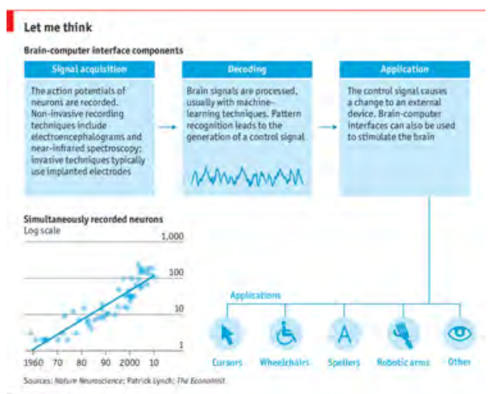
Researchers at the same university have used changes in blood oxygenation in the brain to reconstruct, fuzzily, film clips that people were watching. Now imagine a device that could work the other way, stimulating the visual cortex of blind people in order to project images into their mind's eye.

If the possibilities of BCIs are enormous, however, so are the problems. The most advanced science is being conducted in animals. Tiny silicon probes called Neuropixels have been developed by researchers at the Howard Hughes Institute, the Allen Institute and University College London to monitor cellular-level activity in multiple brain regions in mice and rats. Scientists at the University of California, San Diego, have built a BCI that can predict from prior neural activity what song a zebra finch will sing. Researchers at the California Institute of Technology have worked out how cells in the visual cortex of macaque monkeys encoded 50 different aspects of a person's face, from skin colour to eye spacing. That enabled them to predict the appearance of faces that monkeys were shown from the brain signals they detected, with a spooky degree of accuracy. But conducting scientific research on human brains is harder, for regulatory reasons and because they are larger and more complex.

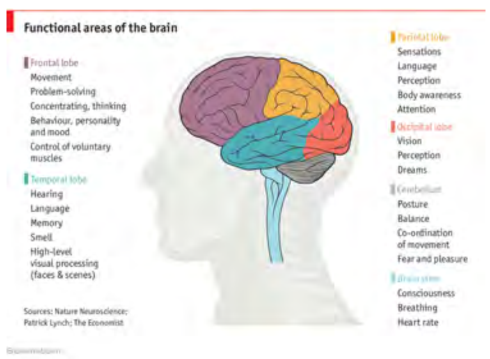
Even when BCI breakthroughs are made on humans in the lab, they are difficult to translate into clinical practice. *Wired* magazine first reported breathlessly on the then new BrainGate system back in 2005. An early attempt to commercialise the technology, by a company called Cyberkinetics, foundered. It took NeuroPace 20 years to develop its technologies and negotiate regulatory approval, and it expects that only 500 people will have its electrodes implanted this year.

Current BCI technologies often require experts to operate them. "It is not much use if you have to have someone with a masters in neural engineering standing next to the patient," says Leigh Hochberg, a neurologist and professor at Brown University, who is one of the key figures behind BrainGate. Whenever wires pass through the skull and scalp, there is an infection risk. Implants also tend to move slightly within the brain, which can harm the cells it is recording from; and the brain's immune response to foreign bodies can create scarring around electrodes, making them less effective.

Moreover, existing implants record only a tiny selection of the brain's signals. The Utah arrays used by the BrainGate consortium, for example, might pick up the firing of just a couple of hundred neurons out of that 85bn total. In a paper published in 2011, Ian Stevenson and Konrad Kording of Northwestern University showed that the number of simultaneously recorded neurons had doubled every seven years since the 1950s (see chart). This falls far short of Moore's law, which has seen computing power double every two years.



Indeed, the Wyss Centre in Geneva exists because it is so hard to get neurotechnology out of the lab and into clinical practice. John Donoghue, who heads the centre, is another of the pioneers of the BrainGate system. He says it is designed to help promising ideas cross several "valleys of death". One is financial: the combination of lengthy payback periods and deep technology scares off most investors. Another is the need for multidisciplinary expertise to get better interfaces built and management skills to keep complex projects on track. Yet another is the state of neuroscience itself. "At its core, this is based on understanding how the brain works, and we just don't," says Dr Donoghue.



Me, myself and AI

This odd mixture of extraordinary achievement and halting progress now has a new ingredient: Silicon Valley. In October 2016 Bryan Johnson, an entrepreneur who had made a fortune by selling his payments company, Braintree, announced an

investment of $100m in Kernel, a firm he has
founded to "read and write neural code". Mr Johnson reckons that the rise of artificial intelligence (AI) will demand a concomitant upgrade in human capabilities. "I find it hard to imagine a world by 2050 where we have not intervened to improve ourselves," he says, picturing an ability to acquire new skills at will or to communicate telepathically with others. Last February Kernel snapped up Kendall Research Systems, a spinoff from the Massachusetts Institute of Technology (MIT) that works on neural interfaces.

Kernel is not alone in seeing BCIs as a way for humans to co-exist with AI rather than be subjugated to it. In 2016 Elon Musk, the boss of SpaceX and Tesla, founded a new company called Neuralink, which is also working to create new forms of implants. He has gathered together an impressive group of co-founders and set a goal of developing a BCI for clinical use in people with disabilities by 2021. Devices for people without such disabilities are about eight to ten years away, by Mr Musk's reckoning.

Neuralink is not saying what exactly it is doing, but Mr Musk's thinking is outlined in a lengthy post on *Wait But Why*, a website. In it, he describes the need for humans to communicate far more quickly with each other, and with computers, if they are not to be left in the dust by AI. The post raises some extraordinary possibilities: being able to access and absorb knowledge instantly from the cloud or to pump images from one person's retina straight into the visual cortex of another; creating entirely new sensory abilities, from infrared eyesight to high-frequency hearing; and ultimately, melding together human and artificial intelligence.

In April it was Facebook's turn to boggle minds as it revealed plans to create a "silent speech" interface that would allow people to type at 100 words a minute straight from their brain. A group of more than 60 researchers, some inside Facebook and some outside, are working on the project. A separate startup, Openwater, is also working on a non-invasive neural-imaging system; its founder, Mary Lou Jepsen, says that her technology will eventually allow minds to be read.

Many BCI experts react to the arrival of the Valley visionaries by rolling their eyes. Neuroscience is a work in progress, they say. An effective BCI requires the involvement of many disciplines: materials science, neuroscience, machine learning, engineering, design and others. There are no shortcuts to clinical trials and regulatory approval.

In all this, the sceptics are right. Many of the ambitions being aired look fantastical. Still, this is a critical moment for BCIs. Vast amounts of money are pouring into the field. Researchers are trying multiple approaches. Mr Musk in particular has a track record of combining grandiose aspirations (colonising Mars) and practical success (recovering and relaunching rockets via SpaceX).

To be clear, "The Matrix" is not imminent. But BCIs may be about to take a big leap forward. For that to happen, the most important thing is to find a better way of connecting with the brain.

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