MIND OVER MATTER

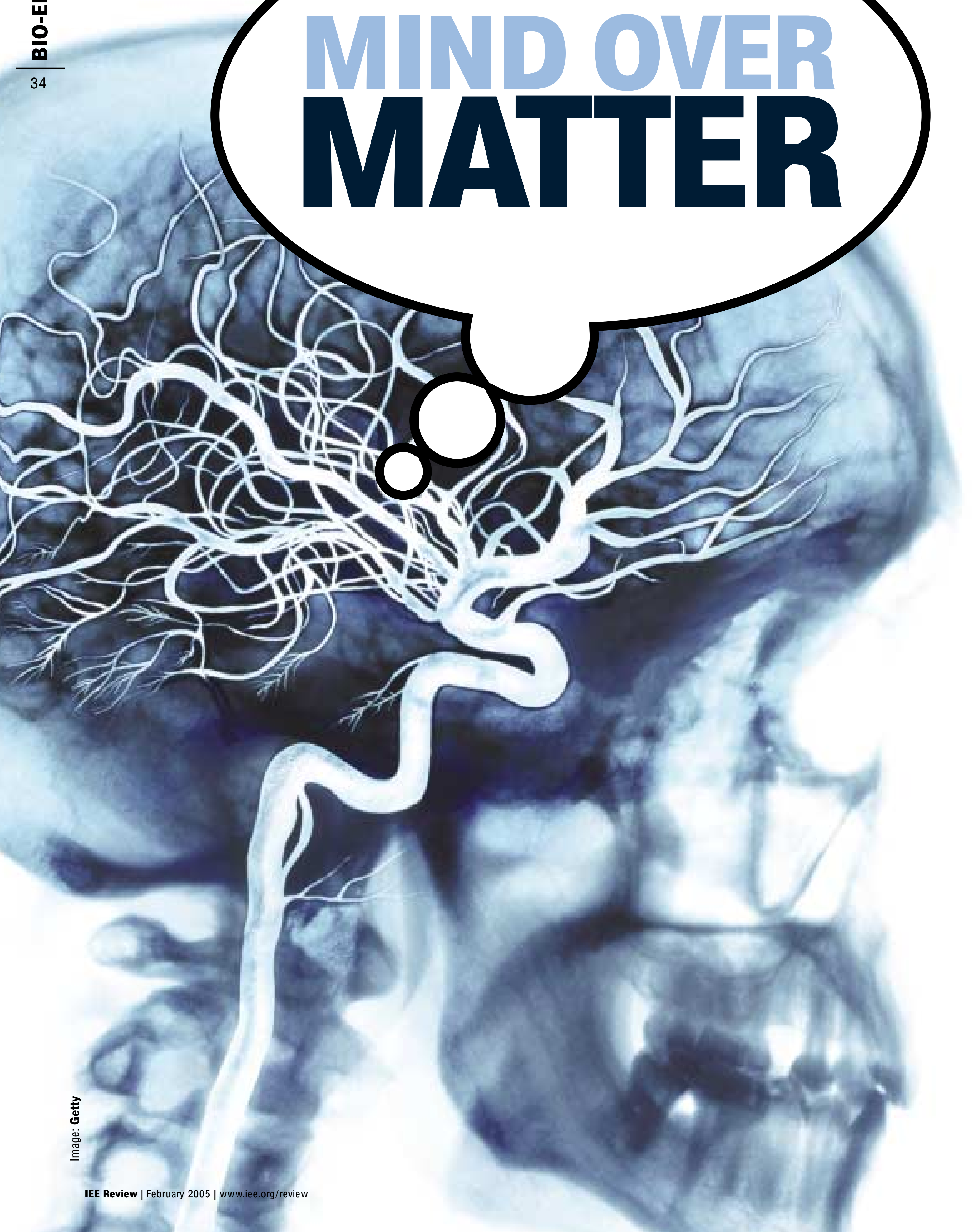


Image: Getty

Moving things with our minds is now becoming possible thanks to neuroscience and some good engineering – but more remains to be done

By Sunny Bains

IT'S NOT DIFFICULT for an engineer to understand why a spinal cord injury can be so devastating. The brain makes the decision about where and when to move, and the spinal cord operates as both communications channel and control system, implementing that decision. If it becomes damaged, the required signals are blocked to some parts of the body, and the brain loses control of them entirely. If the patient is lucky, he or she may still have upper body movement, or be able to communicate by speaking or through basic motions of the eye.

Scientists and engineers have long been working on ways for people with this kind of serious physical impairment to control their environment and interact with the world. Eye-tracking systems that allow computer or wheelchair control are routinely available. But such systems still usually fall short of allowing multitasking – you cannot be using your finger to tap out a message, steer, and operate your drinking straw at the same time.

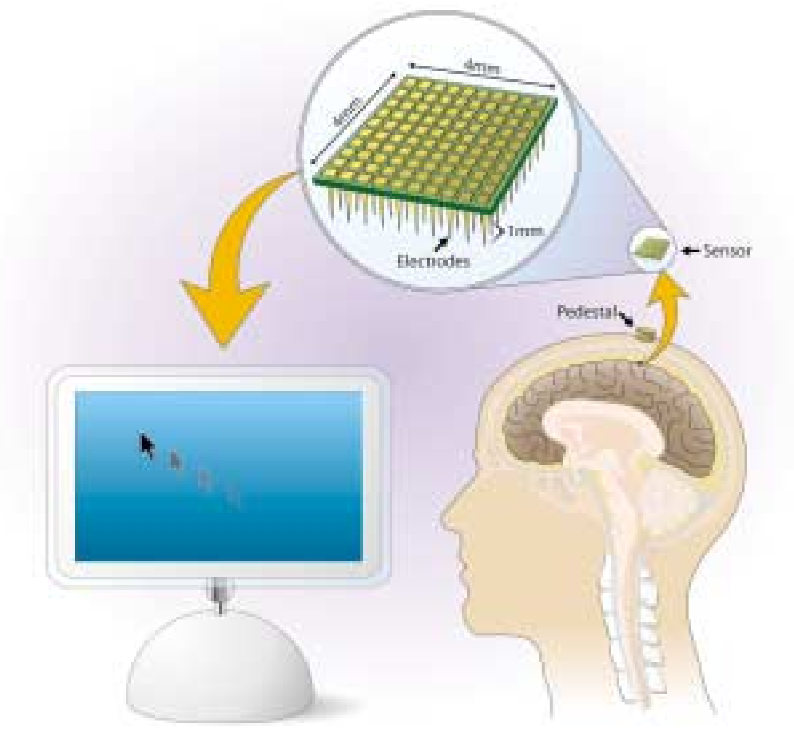
Consequently, researchers are now looking at ways of getting signals straight from the brain to the hardware, to be operated without going through a bodily actuator (assuming one is available). They are doing this by planting electrodes directly into the brain to pick up neural activity, decoding this information, and using it to control machines directly. This involves three major areas of research: neuroscience, to figure out what part of the brain to record and what is to be recorded; electrical engineering, to detect, pre-process, and communicate the neural signals: and information processing, to turn data from the probe into meaningful control signals.

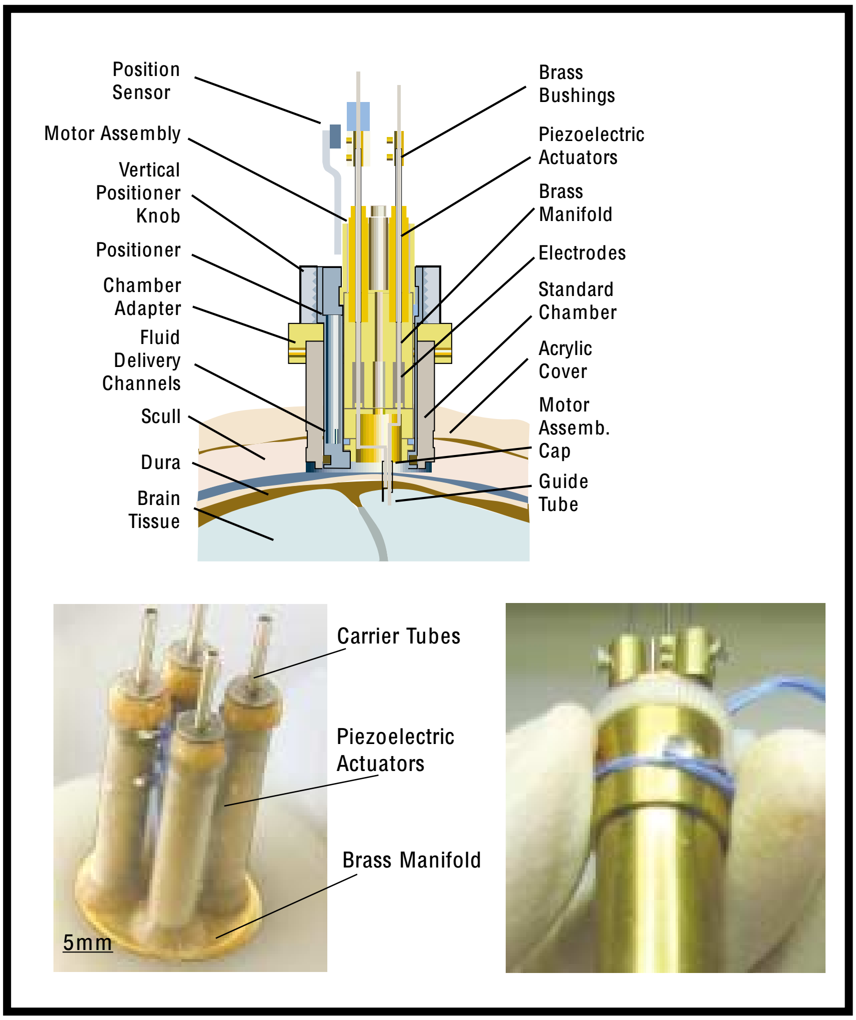
SEE, THINK, DO

Much of the work that has been done so far involves direct control by extracting motor parameters – such as hand position and velocity – from various parts of the brain. For instance, in one set of experiments at Duke University, North Carolina, researchers monitored the frontal and parietal lobes (located roughly in the top half front, and top half centre of the brain, respectively) of monkeys as they used their hands to operate joysticks. According to Dr Jose Carmena, whose work at Duke's NicolelisLab has been partially sponsored by the Christopher Reeve Paralysis Foundation, the monkeys were shown a computer screen and given the task of moving a cursor to intersect with circles that appeared. If it succeeded, it would get a drink of juice. During this phase of the experiment, researchers monitored both the position of the hand (joystick) and the neural activity of the monkey.

In fact, the frontal and parietal lobes – unlike sections of the motor cortex, for example, do not directly send movement signals to the hand. Instead, they are involved with deciding which trajectory to take. This is crucial in the next phase: where the joystick is turned off. The monkey is given the same task but, this time, the cursor is controlled solely by the neural firing. Eventually, the monkey learns that it need →

Below: The BrainGate chip from Cyberkinetics has already been implanted in a human patient and successfully used to control a robot arm and computer





Above: CalTech's microdrive is designed to allow the position of implanted electrodes to be optimised automatically. Shown is: (top) a cross-section of the device illustrating the relative position with respect to skull and brain tissue; (bottom left) the piezoelectric actuators allowing micron and better precision; (bottom right) the loaded motor assembly.

not touch the joystick at all to get the reward: all it has to do is think about how it wants the cursor to move, and it does.

At the California Institute of Technology, Prof Richard Anderson and his colleagues are working on signals with a focus on the monkey's goals, not specific movement paths. By placing electrodes along a path from the extrastriate visual cortex at the back of the brain through the parietal reach region, and on to the motor cortex at the front, they were able to decode not the planned movement itself, but the intention and goal of that move. The eventual aim of using such 'cognitive-level' signals is that they free the user from the need to worry about implementation. Smart-limbs and other machines will work out how to make movements or perform tasks efficiently; all the person needs to do is decide what they want done. Researchers at Stanford University are working on a similar approach.

PICKING YOUR BRAIN

Though it may sound like the technology is already up and running, there is much work to be done before it can be used to aid patients long-term. One problem is very basic: how do you find the 'right' location for neural recording and optimise the amount of signal you are receiving despite tissue migration, inflammation, or cell death? Until now, the answer has been, 'With great difficulty'. Initially, finding the right position was more a question of luck than anything else, because the electrodes had to be placed as part of a monolithic array: researchers could only hope that a decent number of the detectors were in the right place. Later, microdrives were developed that allowed each electrode to be positioned independently, but this was also problematic. Researchers had to carefully position the probes on first implantation and then hand-tweak again on a regular basis in order to optimise the signal.

The CalTech team decided that the best way to tackle this problem was to design a probe that would optimise itself using a neural feedback. Their design uses mini piezoelectric actuators that can move four electrodes over a 5mm range with micron precision, and sufficient force to push through the brain matter surrounding them. Autonomous positioning is achieved using an algorithm that detects the incoming signal and then processes it to produce a figure of merit for the current probe location. This information is then used to optimise the probe position. Though the system works, it may be difficult to scale up – the current design only has four electrodes and hundreds or thousands are necessary.

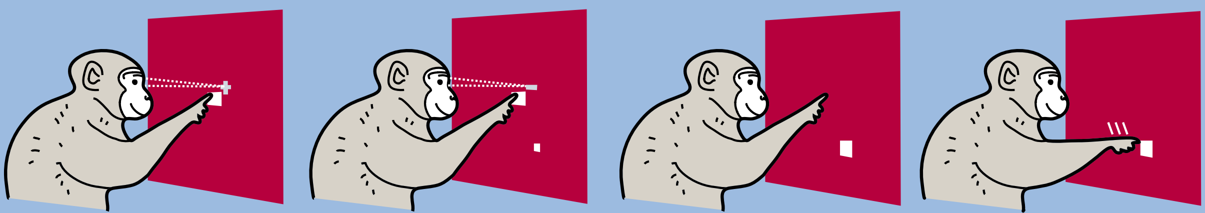
After signals have been detected, the next job is to get them off the chip so they can be decoded. Clearly, the ideal system won't use wires and, to this end, several groups have been working with low-power telemetry systems. Since electrode arrays can have hundreds or thousands of pins, this could represent a communications bottleneck if the signal were not compressed in some way. Fortunately, the brain has its own compression technique in that the neural signals arrive as a series of spikes. This means that all engineers have to do is recognise these spikes and communicate their arrival time.

This may seem like an easy signal processing problem, but digitally identifying a spike and differentiating it from noise in real-time is not a trivial matter. Not only this, but the input from each individual electrode has to be processed in parallel – in around 10ms (to avoid a disorienting time lag between thought and action). This task becomes even more difficult when you remember that, eventually, the processor will have to be worn by the patient all the time: potentially inside the skull.

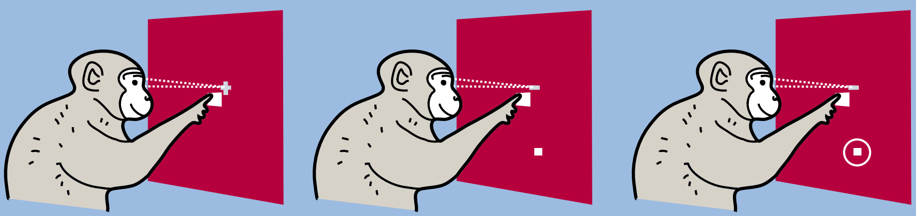
At Stanford University, Prof Krishna Shenoy and his team have been looking into possible solutions, and have obtained promising results using both digital and analogue signal processing. The analogue approach is particularly attractive as the power requirements are many orders of magnitude lower than for digital processing. In collaboration with Prof Reid Harrison →

MONKEY BUSINESS

Training stage



Thought control



One of the Stanford University experiments to allow a monkey to complete a task (and receive a reward) through thought alone.

Training stage: (1) First, while staring at a red fixation point the monkey is trained to touch a point (shown here by the yellow square) on the screen. (2) Next, it is shown the target for its next touch (the smaller square, bottom right). However, it knows it must wait until it receives a 'go' cue before it is allowed to move its hand. (3) The square gets bigger (the 'go' cue), so the monkey knows it's time to touch that point on the screen. (4) Finally, the monkey reaches for the new target, and receives a reward.

Thought control: Here, parts (1) and (2) are identical to the training stage. This time, however, the monkey gets its reward solely by generating the thought patterns corresponding to the 'waiting for the go cue' state (sensed by a neural implants). The system is trained to sense change changes in the brain's activity correlated to this waiting state. In part (3) the state has been recognised, and the computer responds by highlighting the square and providing the monkey with its reward.

In this experiment the monkey is thinking about its goal but not planning the exact movement. This kind of cognitive or goal-oriented command is ideal for situations where a smart machine is available to implement the desire of the patient without needing an exact specification of how the task is to be performed.

TO REALLY GIVE PATIENTS FREEDOM OF ACTION, MANY CHIPS WOULD NEED TO BE IMPLANTED TO SENSE DIFFERENT KINDS OF MOVEMENTS, GOALS, INTENTIONS AND EVEN EMOTIONS

at the University of Utah, they've already built and tested one proof-of-concept analogue processor – with good results – and are now in the process of building a second-generation device.

WHAT DOES IT ALL MEAN?

Once the activity of the selected group of neurons has been read, the last step (before sending control codes to the limb, wheelchair, or computer) is to decipher them. John Donoghue is a professor at Brown University in Rhode Island, and the founder of Cyberkinetics, one of the first companies to get US Government approval to implant neural prosthetics into humans. His team works on output from neurons in the motor cortex, particularly those involved with sending control signals to the hand. To this end, they have developed a new algorithm that allows them to decode the neural signals in real-time.

In the new algorithm, each of the received neural spike rates is considered to encode one hand-movement-related parameter. The complete set of neural spike rates is treated as a Gaussian mixture (i.e. it's assumed each spike reading has been corrupted by Gaussian noise), with each firing rate (hand position/movement) having some probability of occurring. By modelling these probabilities and allowing their values to change over time the system learns to associate firing patterns with specific hand movements.

The Cyberkinetics work has been very successful and, at the end of 2004, the company announced that it had implanted a chip in the first of a set of five paralysed human patients who were to undergo trials of the technology. According to Donoghue, "The patient can use the system to navigate through computer software programs, adjust environmental controls (turn on/off or adjust TV channel or room lights), and control a robotic hand with no more effort than is required for usual hand motions in able-bodied humans."

THE NEXT STEP

According to Richard Anderson from CalTech, one of the next important steps will be to exploit the signals from many different brain areas rather than just sections related to specific types of movement. He points out that, just as a communications bottleneck occurs with a partly-paralysed person (i.e. you can only use your hand for one task at a time), the same will happen with a neuroprosthetically-controlled limb. To really give patients freedom of action, many chips would be implanted to sense different kinds of movements, goals, intentions, and even emotions.

But both he and John Donoghue agree that the first major obstacle to the success of the technology is the engineering of the probes themselves. They must be designed so that they are wireless, implantable (and operational) over a lifetime, and able to adapt to changing brain signals and conditions. If engineers can deliver, they have a long queue of potential customers. ■

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