the crust (at a depth of about 25 km), then the underlying part of the beam could be much thicker, extending into the mantle.

A more fundamental problem is that geologists have surprisingly little to go on when it comes to understanding the mantle, and there is an embarrassingly large gap between laboratory experiments and the behaviour of rocks under real geological conditions. To compound the problem, McKenzie and Fairhead's results[6] fly in the face of scores of other studies: studies conducted in northern India and elsewhere suggest much greater values of beam thickness, up to several times the thickness of the crust, plunging geophysicists into an intense argument about the significance of this discrepancy[7].

In any case, the outer part of the Earth is almost certainly not a single elastic beam, but is more likely to be formed from a number of distinct and separated horizontal layers. And it can be argued that where there are load-bearing regions, the occurrence of earthquakes doesn't necessarily follow — rocks can be plastic, even viscous, rather than brittle, and still offer considerable resistance to deformation. Indeed, earthquakes, in which rocks really are breaking, could be taken as a sign of intrinsic weakness rather than just excessive strain. And a wet mantle remains as speculation: if instead it's dry, it could actually have considerable strength.

Jackson[1] has bravely stuck his neck out and triggered a vociferous but vital debate. The way forward, once geophysicists have settled their differences about measuring elastic-beam thicknesses, must lie in a renewed effort to find out what the Earth's mantle is really like. The study of rare chunks of mantle rock, brought up in volcanoes, combined with the development of better ways to measure mantle temperatures, may prove critical in this respect. Looking below the crust is not easy, but the rewards in terms of understanding our planet will be worth the effort. ■

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Applied physics

Terahertz power

Mark Sherwin

Although radiation at terahertz frequencies has many uses, most sources cannot generate terahertz beams with great power. Magnetic manipulation of energetic electrons inside a particle accelerator offers a solution.

This page emits a broad spectrum of electromagnetic radiation, including frequencies in the region of one terahertz (1 THz = 10^{12} Hz). You cannot see this terahertz emission because its frequency is about 300 times smaller than the limit of human vision. Neither can you feel it: the total intensity emitted at all frequencies below 1 THz is less than a millionth of a watt per square centimetre. Not only this page, but all of the objects around you emit terahertz electromagnetic waves in all directions as 'black-body radiation'.

Terahertz beams much brighter than black-body radiation are required for scientific and technological applications, ranging from the imaging of biological and other materials[1,2] to manipulating quantum states in semiconductors[3]. On page 153 of this issue, Carr *et al.*[4] report the generation of a beam of radiation that contains a broad spectrum of frequencies up to about one terahertz with an average power of 20 W. Such a beam has never previously been created; Carr *et al.* have opened the door to new investigations and applications in a wide range of disciplines.

Researchers have at their disposal an increasing number of sources of coherent terahertz radiation — that is, terahertz radiation with a well-defined phase, such that it can be tightly focused. Lasers that can generate pulses of visible or near-infrared light (around 10^{14}–10^{15} Hz) with a duration less than 10^{-12} s are increasingly common, and can, with small incremental costs, be used to generate terahertz radiation[5].

One common method is as follows. An electric field of about 10^6 V cm^{-1} is generated in a high-resistance semiconductor by applying a d.c. voltage between a pair of electrodes bonded to its surface. An ultrafast laser pulse illuminates the semiconductor between the electrodes, creating a large density of mobile charge carriers (electrons and 'holes') through an effect that is closely related to the photoelectric effect used in solar cells. These charge carriers, sensing the large electric field, accelerate at roughly 10^{17} m s^{-2} — compare that to the gravitational acceleration felt by an object dropped near the Earth's surface, of 10 m s^{-2}. All accelerating charges emit electromagnetic radiation. These charge carriers, reaching their maximum velocity in less than 10^{-12} s, emit a single electric-field pulse shorter than 10^{-12} s that contains a broad range of frequencies, up to a few terahertz. Typically, the average power generated by this method is less than 10^{-6} W. But as this power is in a stable, coherent beam with well-known temporal characteristics, it can be used for spectroscopy with high spectral resolution and excellent signal-to-noise ratio, and even for imaging[3]. The drawback in imaging, however, is that it is usually necessary to scan the beam spot over the object in question, which is much too slow for video-rate image acquisition.

Carr *et al.*[4] also use accelerating electrons to generate their 20-W beam of broadband terahertz radiation. But rather than being trapped inside a semiconductor, these electrons are travelling in a vacuum at nearly the speed of light — inside an accelerator at the Jefferson Laboratory in Newport News, Virginia. The electrons are grouped in bunches that are so small they whiz past an observer in 0.5×10^{-12} s. As long as a bunch of electrons travels in a straight line, it does not accelerate or emit light. But a strong magnetic field can deflect the bunch: if its trajectory is bent along a circular arc of radius 1 m, the associated acceleration causes the bunch to emit a 500-fs pulse (1 fs = 10^{-15} s) of electromagnetic radiation with a peak power of roughly 10^6 W, a peak frequency of about 0.6 THz, and detectable radiation up to several terahertz. When electron bunches are generated at the maximum rate of 37 million each second, the average power in the beam reaches roughly 20 W. In fact, the authors even needed to reduce the power by a factor of 550 to bring the generated signal back within the dynamic range of their equipment.

The 20-W broadband beam complements other sources of terahertz radiation. These include the broadband sources based on ultrafast lasers, discussed above, that come in two types. The first emits pulses with peak powers that are similar to those reported by Carr *et al.*[4], but the maximum repetition rate is only 10^3 Hz, compared with 4×10^7 Hz for the Jefferson Lab source, and the resulting average power is roughly 10^{-3} W (ref. 6). The other type of source emits terahertz pulses with a repetition rate of 10^8 Hz, but an average power of less than 10^{-6} W (refs 1, 3).

There are also sources that emit radiation at well-defined frequencies. These include the quantum-cascade laser[7], which produces pulses with a peak power of 0.002 W at around 4 THz; microwave oscillators[8], whose frequency can be multiplied by nonlinear devices (10 s of continuous power at the microwatt level and below 2 THz); and free-electron lasers that reach 10^3–10^6 W of peak power[9]. Each of these sources has already found its own applications and users.

As with any new technology, it is difficult to predict the most important applications — the inventors of the laser did not envisage barcode scanners. The authors speculate that the large peak power could be used for the study of new nonlinear phenomena in advanced materials and devices, and that the large average power could allow “full-field, real-time image capture” — in effect, terahertz movies. Another possibility is that the large average and peak powers could be used to manipulate and alter materials, chemical reactions and biological processes. Perhaps, as you bask in the weak terahertz radiation emitted by this page, you will think up the ‘killer’ application for the new terahertz source. ■

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Neuroscience

Single-neuron mnemonics

Barry W. Connors

How can you remember what you’ve just read or seen or done? The issue of short-term memory has vexed neuroscientists for more than half a century; a new study adds an unexpected piece to the puzzle.

Even the minutiae of life must be remembered, however fleetingly. Who just called me? Which journal am I reading? What were the words that preceded this question mark? And as new challenges appear, it also helps to forget the trivia of the recent past. The capacity to temporarily retain small quantities of information is loosely called short-term or working memory, and is a basic function of the brain. Yet the mechanisms underlying this ability remain a mystery. Long-lasting forms of memory apparently require molecular or structural changes in nerve cells, but short-term memory is a dynamic, ephemeral process that has not yielded to molecular characterization. A venerable theory is that short-term memories are held by interconnected groups of neurons that fire persistently because they excite one another recursively. The work of Egorov and colleagues[1], described on page 173 of this issue, thickens the plot. These authors found that a single, isolated neuron, when stimulated briefly, could generate sustained increases in its electrical activity that were graded in intensity and readily reversible. In other words, one such neuron could quickly remember (and forget) numerous bits of information.

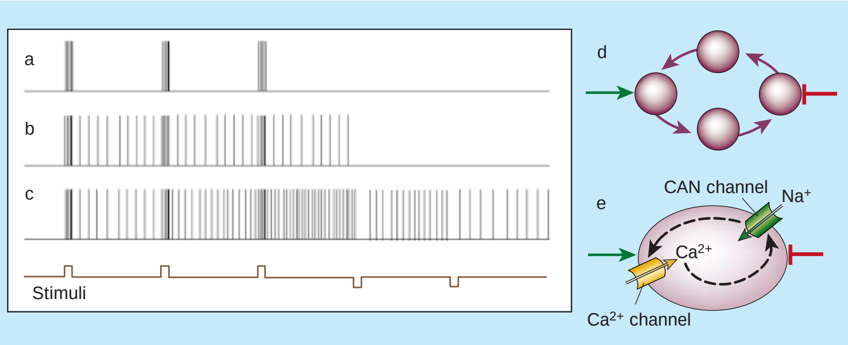

Figure 1 **Memory and the single neuron. Neurons signal their activity by generating brief spikes of membrane voltage; the rate and timing of spikes carry information.** a, **Most neurons respond to excitatory stimuli (upward steps in the line below** c**) by spiking only as long as each stimulus lasts.** b, **Very rare neurons are bistable: brief excitation leads to persistent spiking, always at the same rate; brief inhibition (downward steps in the line below** c**) can turn it off.** c, **Multistable neurons persistently increase or decrease their spiking across a range of rates in response to repeated brief stimuli.** d, **In a reverberatory network model of short-term memory, an excitatory stimulus (green arrow) leads to recursive activity (purple arrows) in interconnected neurons (purple circles). Inhibitory stimuli (red bar) can halt the activity.** e, **Egorov *et al.*[1] suggest that graded persistent activity in single neurons (as in** c**) might be triggered by a pulse of internal Ca^{2+} ions that enter through voltage-gated channels; Ca^{2+} then activates CAN channels, through which an inward current (largely comprising Na^+ ions) enters, persistently exciting the neuron. The positive feedback loop (black broken arrows) may include numerous, unknown signalling mechanisms.**

Any theory of short-term memory must explain how it is initiated, why it persists, what makes it specific, and how it ends. Individual neurons had previously seemed too inflexible for the job. Most neurons, when isolated from the rest of the brain, increase their activity only during a stimulus (Fig. 1a), so it’s hard to see how they could be involved in remembering that stimulus. A few neurons are bistable — brief stimuli can switch them between two persistent states (Fig. 1b) — and, like electronic flip-flops, such neurons can in principle serve as memory media[2]. But they are exceedingly rare in mammals.

Moreover, in the brains of animals that are performing certain tasks, neurons seem to do something even more complex[3]. In a typical experiment, a monkey is trained to remember a short sensory cue, for example a coloured flash of light, then wait patiently during a variable delay, and finally respond to the remembered cue in a manner appropriate to the task. Groups of neurons in many areas of the brain’s cerebral cortex both increase and sustain their firing rates throughout the delay period, suggesting that they are involved in remembering the stimulus. Such ‘delay neurons’ often have distinct stimulus preferences, persistently firing faster after the cue is, say, green rather than red.

How might such delay activity come about? In the 1930s, Rafael Lorente de Nó pointed out[4] the dense interconnections between neurons throughout the brain. He suggested that a brief stimulus might excite a few neurons, which could excite other neurons, such that neural activity ricochets around, or reverberates, even after the original stimulus has disappeared (Fig. 1d). The reverberations would probably be fragile and easily disrupted by another salient stimulus. Although born in the primordial ooze of theoretical neuroscience, the notion of persistently active neuronal networks — famously elaborated by Karl Lashley and Donald Hebb[5] in the 1940s — still holds sway. Contemporary theoreticians have modelled formal, clever variations of it that explain a range of specific behaviours[6–9]. In most models each neuron is given mundane intrinsic properties (such as those seen in Fig. 1a), and delay activity emerges only as a consequence of the interactions among many neurons.

But the findings of Egorov *et al.*[1] suggest that this is not the only possible explanation. These authors studied a region of the rat brain called the entorhinal cortex, which is essential for working memory during certain behaviours. They first exposed slices