other recent studies that distinguish between forgetting and false memories due to damage in other parts of the MTL system offer a broader perspective. In these experiments, rats initially study items chosen from a large list each day, and then investigators measure their memory performance in terms of “hits” (correct identifications of stimuli that were on that study list) and “false alarms” (errors where subjects incorrectly judge new stimuli as appearing on the study list). Damage to the hippocampus results in a decrease in hits with no effect on the false alarm rate (4), indicating that the deficit is due to forgetting rather than false memories—the opposite of the pattern observed by McTighe et al. In contrast, damage to the prefrontal cortex results in an increase in false alarms and no effect on the hit rate (5), similar to the pattern observed by McGinty et al. These studies suggest that distinguishing forgetting from false memory provides researchers with a powerful tool for identifying the contributions of different brain areas to memory.

Furthermore, these diverse findings can be integrated into a model of the anatomical pathways of MTL system and its interactions with cortical areas (see the figure) (6). The perirhinal cortex is the end point of the so-called “what” stream, a cortical hierarchy of perceptual processing areas that represents information about objects (7). There is also a parallel “where” stream in the cortex, ending in the MTL within the parahippocampal area, which represents the spatiotemporal contexts in which objects have been experienced. These streams merge within the hippocampus, which represents relationships between objects and between objects and their context. In this model, the role of the perirhinal cortex is to bind perceptual features into representations of whole objects, and make these representations resistant to perceptual interference—just as McGinty et al. describe. The hippocampus normally encodes and retrieves representations of the objects and context when cued, and damage to the hippocampus prevents this retrieval, resulting in forgetting. The prefrontal cortex normally receives that information from feedback pathways through the MTL, and monitors the match between object and context memories (“Is this object from today’s list?”). Lacking that monitor, the animals cannot tell whether an object is from today’s list or a previous list—leading to the increase in false memories following prefrontal damage.

A decade ago (2), available evidence led to the conclusion that different forms of memory should be viewed as the outcome of plasticity within systems organized to perform particular information processing functions. The MTL’s information processing functions, however, were unclear. In their study, McGinty et al. offer a partial answer: The MTL’s perirhinal cortex binds featural elements into cohesive configurational memories, and this function is supported by known plasticity mechanisms (8). The hippocampus and prefrontal cortex, as well as other key brain areas of this system, also contribute directly to memory through plasticity in their particular information processing tasks. These findings, then, support the view that there is a dedicated MTL memory system. They also further our understanding of that system as a set of specialized areas that interact to coordinate the information processing functions required for successful memory.

References

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PERSPECTIVES

MATERIALS SCIENCE

High-Temperature Rubber Made from Carbon Nanotubes

Yury Gogotsi

Carbon nanotubes have been among the most studied materials for the past two decades (1); they display several remarkable properties, such as extremely high tensile strength and electrical conductivity. On page 1364 of this issue, Xu et al. (2) report another case of extreme mechanical performance of a carbon material—viscoelastic behavior of nanotubes in a wide temperature range—that no other solid has shown so far.

Viscoelasticity is the ability of a material to dissipate energy through viscous behavior (think honey) and reversibly deform through elasticity (think rubber band). Polymer foam earplugs are a typical viscoelastic material; they conform to any shape of ear channel but fully recover to the original form after being pulled out. Viscoelasticity is exhibited by a large number of materials (3), including amorphous and semicrystalline polymers, biomaterials, crystalline materials experiencing reversible phase transformations, and some metallic alloys.

Viscoelastic behavior is determined by measuring stress-strain curves: The material is pushed on or pulled at a given force (stressed), and deformation (strain) is measured. A viscoelastic material exhibits “memory” (hysteresis) effects in its stress-strain behavior. For example, the amount of stress needed to maintain the same level of strain will drop over time, and for a given stress, the material will continue to deform.

The material reported by Xu et al. is a special case of a viscoelastic material; it behaves like rubber under moderate deformations. Rather than store energy in permanent deformation, like a bent metal part, a rubber releases the energy when the applied force is removed. Viscoelastic behavior of nanotubes has been observed for vertically aligned brushes and foams of tubes (highly intertwined random networks) tested at room temperature (4–7). The groups of Gogotsi and Greer independently observed buckling and irreversible compressibility...
Nanotube arrangements leading to rubbery materials. Images are from atomistic models of the displacement of entangled nanotubes relative to each other or temporary collapse (flattening) of thin tubes. (A) Three nanotubes (single-walled, double-walled, and triple-walled) are shown in contact with each other and interacting only by van der Waals forces. (B) The dumbbell shape of the collapsed nanotube decreases the distance between the walls to the interplanar spacing of graphite and temporarily creates van der Waals bonding in the middle area of the tube. (C) A hypothetical material consisting of interlocking nanotube rings that would be expected to display viscoelastic behavior.

of various nanotube architectures at large strains (4, 5). The material developed by Xu et al. is a random network of long, interconnected and entangled carbon nanotubes (a mix of single-, double-, and triple-walled tubes) that exhibits rubberlike behavior over a very wide temperature range. They tested their samples from –196°C to 1000°C, but the carbon-carbon bonds in graphitic walls of nanotubes are stable above 1500°C. Thus, an even broader temperature range can be expected for viscoelastic response, at least in a non-oxidizing environment. The demonstration of viscoelastic behavior and large reversible deformation for a wide temperature range makes the random, entangled nanotube network described by Xu et al. a versatile viscoelastic material. It can dampen vibrations and absorb impact at extremely low or very high temperatures, where neither a perfectly elastic rubber nor a metallic felt or wool would work.

The viscoelastic behavior of the most typical viscoelastic materials, such as polymers, is temperature-dependent; the molecular rearrangement of polymer chains, a mechanism governing viscoelasticity, is a thermally activated process. Xu et al. suggest that, unlike polymers, thermal stability in their material stems from energy dissipation through the zipping and unzipping of carbon nanotubes upon contact (see the figure, panel A). An additional mechanism of energy dissipation is the flattening and recovery of nanotubes (see the figure, panel B). For the tubes with inner diameters of 3 to 5.5 nm, the collapsed state is metastable and is separated from the energetically favorable cylindrical shape by an energy barrier (8). The barrier decreases with the diameter and disappears when the single-walled tube diameter is smaller than 3 nm.

The entangled nanotube material is a kind of versatile rubber that could be used in cold interstellar space or inside a high-temperature vacuum furnace. It may not be easy to find a material with viscoelastic properties similar or superior to those reported by Xu et al. Thin-walled carbon nanocapsules (onions or giant multishell fullerenes) may offer reversible compressibility (9) similar to nanotubes (see the figure, panel B), but only fibrous materials can offer rubberlike behavior and such a large reversible deformation under tension. Graphene foam would lack elastic recovery because there would not be a driving force necessary to accommodate it; moreover, all carbon foams and porous carbons—even those that show plasticity and elastic recovery at the nanoscale and microlscale (10)—fail in brittle manner when subjected to macroscopic deformation. Nanotube foams may form an incompressible material showing rubberlike behavior, but such an arrangement of carbon rings (see the figure, panel C) remains hypothetical.

Many high-temperature applications of materials expose them to oxidizing conditions. Most small-diameter nanotubes burn at temperatures close to 400°C, so very-high-temperature applications may only be possible in a vacuum or protective (reducing) atmosphere. Incorporating these nanotube rubbers into commercial products will depend in part on lowering of material costs, but note that the cost and production volume issues have been largely resolved for multiwalled tubes that are at least 5 nm in diameter. With further developments, nanotube materials may find use not only in space vehicles but also in down-to-earth applications, such as wrinkle-free textiles or viscoelastic shoe insoles that reduce mechanical shocks.

References and Notes
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