of the growing axons to the midline. The axon tips then grow toward and into the midline. After the axons cross the midline, Robo3 expression is down-regulated and Robo1 becomes strongly expressed. The repellent effects of Slit and silencing of the attractant Netrin ensure that the growing axons leave the midline and do not cross it again.

The Jen *et al*. (*1*) and Sabatier *et al*. (*2*) studies show that mammalian Robo3 differs from other Robo proteins in two crucial respects. First, it is a chemoattractant and not a repellent to axons trying to cross the midline. If Robo3 is expressed in the hindbrain, axons cross the midline. If it is not expressed, they do not cross the midline. Second, human and mouse Robo3 lack the CC1 domain, which has been found in all other Robo proteins. CC1 is one of four conserved cytoplasmic domains and enables Robo proteins to bind to DCC and silence the chemoattractant effects of Netrin (see the figure) (*7*). Thus, although Robo3 itself may not be a chemoattractant, its expression allows Netrin to act as a chemoattractant for growing axon tips.

Many questions remain about the control of axon crossing. For example, what is the mechanism controlling Robo3 expression? Was the loss of the CC1 domain a specific event during mammalian evolution that led to a new function for Robo3? Despite these unanswered questions, the work of Jen *et al*. and Sabatier *et al*. has brought us closer to a fundamental understanding of this complex developmental pathway.

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PHYSICS

Ion Entanglement in Quantum Information Processing

D. G. Cory and T. F. Havel

Over the past decade, quantum entanglement has been recognized as an increasingly useful property of multiparticle systems (*1*). Schrödinger coined the term entanglement to mean a peculiar mutual quantum interaction in which the properties of two or more physical objects can be correlated, even when separated. Quantum teleportation, error correction, computation, and communication all benefit from (or require) entanglement (*2*). One current challenge for the field of quantum information processing has been to engineer a sufficiently large and complex controllable system in which questions related to entanglement can be precisely explored. On pages 1478 and 1476 of this issue, Roos *et al*. (*3*) and Leibfried *et al*. (*4*) report the creation, control, and potential applications of three-particle entangled states made with trapped ions.

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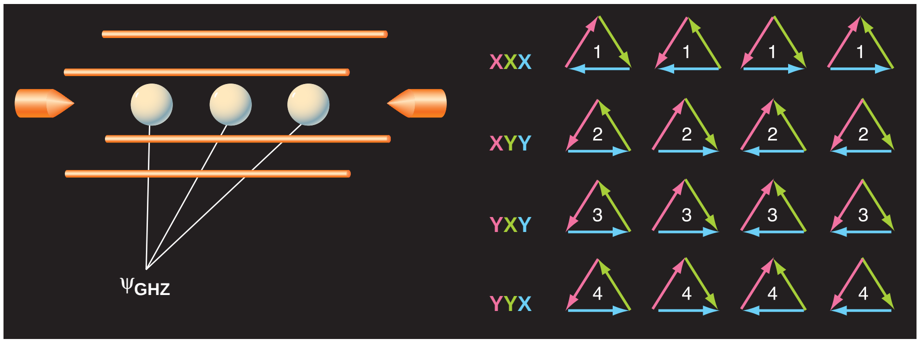
Until recently, most of the laboratory examples of entangling and coherently controlling more than two particles have come from optics and ensemble measurements via liquid-state nuclear magnetic resonance (NMR). Although useful for furthering the development of coherent control methods, these implementations do not scale easily to larger numbers of particles. Whereas limited manipulations of even seven-qubit systems have been possible in liquid-state NMR (*5*), it is particularly important to see the continued development of microscopic systems based on pure-state dynamics, which may lead to scalable quantum computation.

In the studies reported here, both groups created and controlled the three-ion version of a GHZ (Greenberger-Horne-Zeilinger) state (*6*) in an ion trap (see the figure, left). GHZ states are especially important in studying the entanglement of more than two particles because we can explore the entanglement that remains when one particle is measured or lost.

Whereas Kielpinsky *et al.* have previously reported the preparation of the four-ion analog of this state (*7*), here the group was able to both generate the state and have precise control over it. Two-ion entanglement has previously been reported; however, the GHZ state provides a more direct understanding of quantum entanglement (see the figure, right).

Roos *et al*. manipulated the GHZ state to explore the dynamics of the quantum disentanglement eraser suggested previously by Garisto and Hardy (*8*). Although two-particle versions of this can show the consequences of quantum interference, the three-particle GHZ version demonstrates that measurement of the state of one particle can result in entanglement being lost or gained between the remaining two particles. A novel and technically challenging



Trapped and entangled. (Left) Three ions in a trap (*10*) can be efficiently cooled, and via laser addressing, their internal states can be used as quantum memories. Although many ions can be stored, the ongoing challenge is to keep them cold and simultaneously have coherent control. **(Right)** Mermin (*11*) suggested an experiment to show that there is no classical (that is, hidden-variable) description of the GHZ state. The quantum correlation is revealed by making four separate measurements. To demonstrate that these are inconsistent with a classical interpretation, we can visualize the set of possible outcomes as the faces of a tetrahedral die with its edges colored to represent the three qubits. The set of possible outcomes (think of this as one face of the tetrahedral die thrown randomly) are shown. The relative orientations of the arrows correspond to the relative outcomes following measurements of the three particles along the axes indicated (*x* or *y*). Information is stored along the *z* axis. The impossible task is to assemble four (classical) tetrahedra from the above faces with the rules that each tetrahedron includes one each of faces 1 to 4 and that the edges match (in both color and orientation).

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part of the implementation of Roos *et al.* is that they included a rotation of the final two-particle state conditional on the measurement of the first particle. This is an important enabling technology for the field of quantum information processing. For most approaches to fault-tolerant quantum computation, it is easiest to envision the computation running in parallel with measurements of the compounding errors. Then, while the computation is still proceeding, the stored quantum information would be continually corrected on the basis of these measurements. In the demonstrations of quantum error correction to date (*9*), the error correction step was implemented so as to put off all measurements to the end. Although not yet known, it is expected that measurement errors during the computation will scale better than the approach of correcting them all at the end of the computation.

Leibfried *et al.* used the GHZ state to implement an improved precision of measurement. In observing the collective three-particle evolution, they achieved frequency resolution higher than in any corresponding single-particle measurement by a factor of 1.45. Although the theoretical improvement in resolution can be a factor of $\sqrt{3}$, via their careful manipulations of this entangled state they were indeed able to exceed the single-particle Heisenberg limit. So there is already a demonstrable advantage to using entangled states for measurements.

These two complementary studies show the continued progress in engineering quantum systems to perform tasks that are beyond their classical counterparts. They open a new path for coherent control by enabling the control operation to be conditional on measurement, and they point to practical applications for entangled states.

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MATERIALS SCIENCE

Designer Nanotubes by Molecular Self-Assembly

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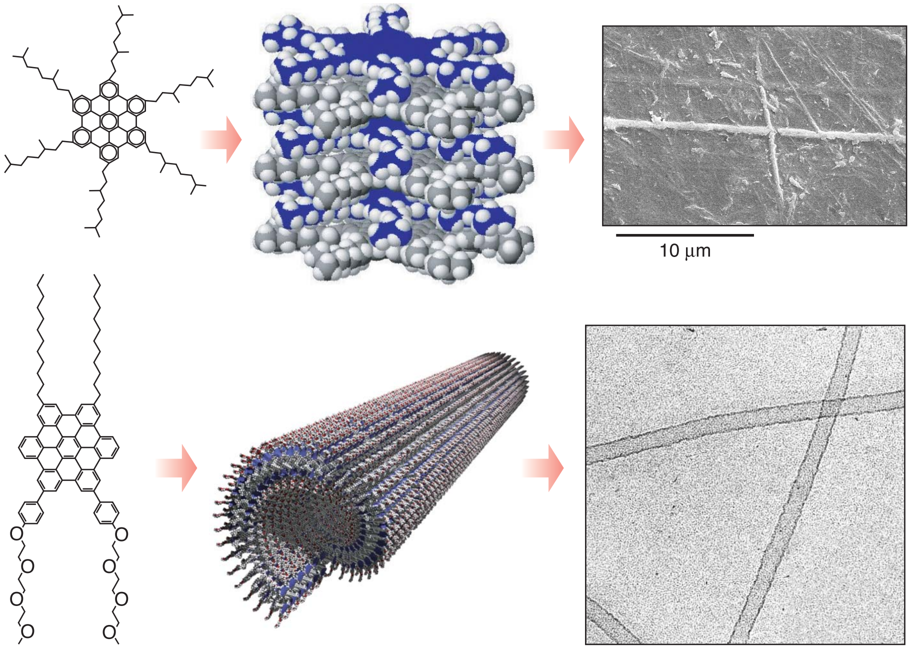
Did you ever see acrobats in the circus balancing spinning plates on bamboo sticks and thereby creating spectacular shapes in apparent defiance of gravity? Clearly, they are overcoming the environmental gravitational forces acting on the plates by precisely positioned and well-controlled centripetal forces. On page 1481 of this issue, Hill *et al.* (*1*) report a similar balancing act in their synthesis of novel nanotubular objects from platelike molecules.

On a molecular scale, the accurate and controlled application of intermolecular forces can lead to new, previously unachievable, nanostructures. This is why molecular self-assembly (MSA) is a highly topical and promising field of research in nanotechnology today. MSA encompasses all structures formed by molecules selectively binding to a molecular site without external influence. With many complex examples all around us in nature (ourselves included), MSA is a widely observed phenomenon that has yet to be fully understood. Being more a physical principle than a single quantifiable property, it appears in physics, chemistry, and biochemistry, and is therefore truly interdisciplinary (*2*).

The problem to date with researching the fundamental physics behind MSAs has tended to be that prime examples of MSAs are mainly found in the biological sciences. Biomolecular assemblies, such as light-harvesting antenna complexes found in some bacteria, are sophisticated and often hard to isolate, making systematic and progressive analyses of their fundamental physics very difficult. What in fact are needed are simpler MSAs, the constituent molecules of which can be readily synthesized by chemists to a high degree of purity—high-quality sample preparation, chemical purity, and known sample history that are paramount in MSA research. These molecules should self-assemble into simpler constructs that can be easily assessed with current experimental techniques.

Weak intermolecular bonds, such as van der Waals bonds, that selectively bind molecules to a site in an assembly are what make MSAs so varied. It would be almost impossible to mimic MSA complexity using synthetic, aggressive chemistry to join molecules together via covalent bonding.



Molecular balancing acts. Examples of MSAs formed with hexabenzocoronenes, from the author's laboratory (above) and from Hill *et al.* (*1*) (below). **(Left)** Molecular structure; **(center)** MSA simulation; and **(right)** scanning and transmission electron microscope images of the respective MSAs.

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