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Quantum Correlation Between Distant Diamonds

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association with disease, the yeast studies indicate that these genes can modulate Aβ toxicity itself. Treusch *et al*. confirmed these findings for many genes, including *PICALM* in *C. elegans*, and for *PICALM* in cultured rat cortical neurons, then gained additional insight from yeast. Aβ compromises endocytic trafficking in yeast, and the subset of modifiers implicated in endocytosis mitigates this deficit.

The Treusch *et al*. studies illustrate that modeling disease in simple organisms like yeast, nematode, and fly can peel away the complexity of human disease to help reveal the core defective processes. The hope is that this may help distinguish causative changes from downstream complications, as targeting the core problem is more likely to arrest disease progression. Further, whereas GWA studies link a chromosomal region to disease, they often do not identify a specific gene or define a causative molecular effect; by contrast, genetic screens can demonstrate that the risk is associated with altered expression of a gene.

These studies highlight that strong collaboration and integration of findings between human geneticists and model organism researchers should be encouraged (see the figure). Model organism systems identify the range of genetic modifiers, whereas the human genetic and genomic data point to those modifiers with greatest impact in patients. The interplay between multiple systems and complementary approaches, such as those used by Treusch *et al*. and others (*10*), promises to elucidate the underlying biology and lead us toward the goal of identifying targets for effective therapeutic intervention.

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PHYSICS

Quantum Correlation Between Distant Diamonds

Entanglement of spatially separated systems is not limited to atomic systems, but can be created between diamond crystals separated by several centimeters.

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Entanglement is a kind of quantum correlation that distinguishes the outcomes of events in the quantum world from those in the classical one. In the classical world, chance outcomes have no strange correlations—the events at one roulette wheel in a casino have no effect on events at the other tables. In a quantum casino, we could imagine that roulette wheels are entangled, so that if one ball dropped on a black number, the ball at the next table must drop on red. The correlation of experimental outcomes created by entanglement is an essential resource for implementation of quantum information processing. Entanglement is often associated with the microscopic world; it is typically fragile and hard to preserve for large systems at macroscopic distances because of decoherence—the consequence from the inevitable coupling between macroscopic objects and their environments. Recent advances in quantum control techniques have allowed entanglement to be observed for physical systems with increasing complexity and separation distance. On page 1253 of this issue, Lee *et al*. (*1*) take an important step in this direction by demonstrating entanglement between oscillation patterns of atoms—phonon modes—of two diamond samples of millimeter size at room temperature, separated by a macroscopic distance of about 15 cm.

Although quantum mechanics provides a more fundamental description of nature, we normally see only classical behavior in our everyday world. Why is this the case? The microscopic systems used to create entanglement work because they have relatively few degrees of freedom for measurement outcomes (spin states might only point up or down), and in some cases, we can isolate the coherent coupling of these states from environmental effects. A macroscopic object like a roulette ball has a huge number of degrees of freedom created by its constituent atoms, and these states are usually strongly coupled with their environment rather than just to each other. At room temperature, thermal excitations also destroy coherence, all of which leads to our observation of classical measurement outcomes (the roulette balls cannot develop correlations in their states that would influence how they drop on the wheels).

Lee *et al*. used the optical phonon mode of small diamonds to carry quantum entanglement. Diamond is a stiff material, and its optical phonon mode has a very high oscillation frequency. It is not readily excited by thermal energy even at room temperature. No cooling was needed to create a pure initial state that is required for entanglement generation. Ultrafast optical technology was used to generate and measure the entangled state before any environmental coupling might destroy it. Once created, the entangled states of the optical phonon mode only survived for about 7 ps in room-temperature diamonds. An ultrafast optical pulse with a delay about 0.35 ps—well within the lifetime of coherence in diamonds—quickly mapped this entanglement out of the solids for experimental detection.

The entanglement was generated and detected with the DLCZ scheme (*2*) for long-distance quantum communication. An ultrafast laser pulse excited one optical phonon mode of the diamond sample and at the same time produced a scattered photon (see the figure) that would entangle phonon states. The DLCZ scheme has been applied in a series of very successful experiments to generate entanglement between distant atomic ensembles (*3*–*5*). This scheme has been adapted to create entanglement between remote single trapped ions (*6*) and to teleport quantum states between matter qubits, the ideal memory for quantum information (*7*).

Lee *et al*. implemented the DLCZ scheme by bringing together the scattered photons from the two samples at a beam splitter, where they could undergo interference. Detection occurred at single-photon counters. If the detector registered one scattered

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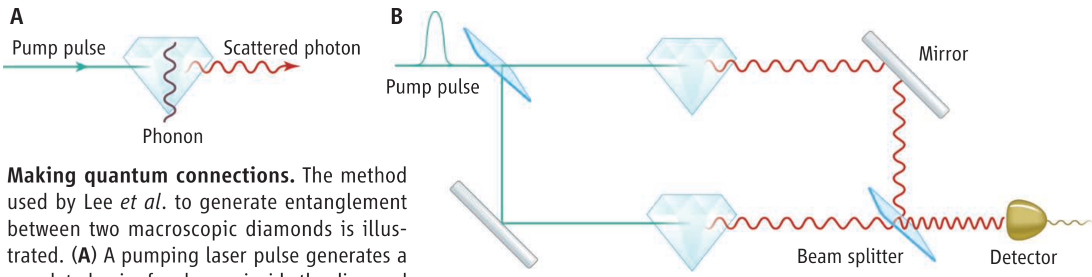
photon, it could have come from either of the diamond crystals in which one phonon was excited. The indistinguishability of these two possibilities during detection means that the two diamond samples coherently shared one phonon, which is the hallmark of a quantum-entangled state.



Making quantum connections. The method used by Lee *et al.* to generate entanglement between two macroscopic diamonds is illustrated. **(A)** A pumping laser pulse generates a correlated pair of a phonon inside the diamond as well as a scattered photon. **(B)** The scattered photons from two diamonds are brought together for interference and detection. When one photon is detected, the two diamonds coherently share a phonon. Thus, the quantum state created has the hallmarks of quantum entanglement.

The entanglement between the two diamond samples was confirmed in experiments in which a second laser pulse de-excited the shared phonon and re-emitted a photon that was subsequently detected. By this method, Lee *et al.* demonstrate that the two diamonds share entanglement at a 98% confidence level. These results provide a striking example that entanglement is not particular to microscopic particles but can manifest itself in the macroscopic world, where it could be used in future studies that make fundamental tests of quantum mechanics.

The demonstration of entanglement in macroscopic systems also has important implications for the ongoing efforts to realize quantum computation and communication. A full-size quantum computer eventually will need to be a macroscopic device in which entanglement is preserved and used over long times and distances. The lifetime of entanglement in the experiment by Lee *et al.* is still too short for many quantum information applications, in part because of the room-temperature environment and the strong coupling of phonon modes in solids. However, the experiment emphasizes an important point, that ultrafast optical technology can alleviate the requirement on quantum coherence time. In future, with improvement of the ultrafast technology, or by using more isolated degrees of freedom in solids—such as as the nuclear spins (*8*) or the dopant rare-earth ions (*9*)—for quantum memory, many more quantum operations could be done within the coherence time of the solids, even at room temperature.

References and Notes

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ECOLOGY

Mathematical Dances with Wolves

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Data and modeling of Yellowstone wolf populations illustrate the complex interrelated ecological and evolutionary responses to environmental change.

In the movie *Dances with Wolves*, a lone wolf facilitates Lieutenant John Dunbar's immersion into the complex culture of the Sioux Indians. This immersion required overcoming multiple cultural barriers. Ecologists and evolutionary biologists face an equally daunting challenge of understanding how environmental change affects ecological and evolutionary dynamics (*1*). Historically, researchers examined these impacts in isolation. However, these dynamics can occur on similar time scales, resulting in a dynamic evolutionary-ecological feedback loop (*2*). Studying these feedbacks directly for long-lived species is often thought to be impractical. On page 1275 of this issue, Coulson *et al.* (*3*) overcome this barrier using data from radio-collared gray wolves and state-of-the-art mathematical models.

The 280 radio-collared wolves studied by Coulson *et al.* are direct descendants of 41 gray wolves reintroduced into Yellowstone National Park between 1995 and 1997 (*4*). This reintroduction was part of a larger effort involving a simultaneous reintroduction in Idaho and a naturally colonized population in Montana. It was extremely successful; by 2010, the Northern Rocky Mountain wolf population had expanded to 1651 individuals (*5*). Individuals within this expanding population vary substantially in body size, coat color, and other observable (phenotypic) traits. Coat color is particularly enigmatic; gray wolves in North America often have black coats, whereas in Eurasia black coats are rare, but the reason for this difference remains unclear (*6*). These traits were recorded for over a decade (from 1998 to 2009) for each collared wolf and their offspring.

To explore the potential ecological and evolutionary responses of the gray wolves to environmental change, Coulson *et al.* fuse integral projection models (IPMs) with classical population genetics. Unlike their matrix model counterparts (*7*), IPMs describe the dynamics of populations with traits that vary continuously, such as body size (*8*), as well as discrete traits, such as coat color (*9*). Traditional IPMs track how the number of individuals with a particular body size changes due to births, deaths, and individual growth. The rules underlying these changes are determined by statistical relationships between the body size of individuals and their vital rates such as fecundity, survivorship, and growth.

In gray wolves, a change at a single location on the genome—the K locus—determines coat color (*10*). To link evolutionary and ecological dynamics, Coulson *et al.* extend the IPM to account for this genetic difference between individuals. As a result, the statistical relationships between individual body size and vital rates become geno-

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