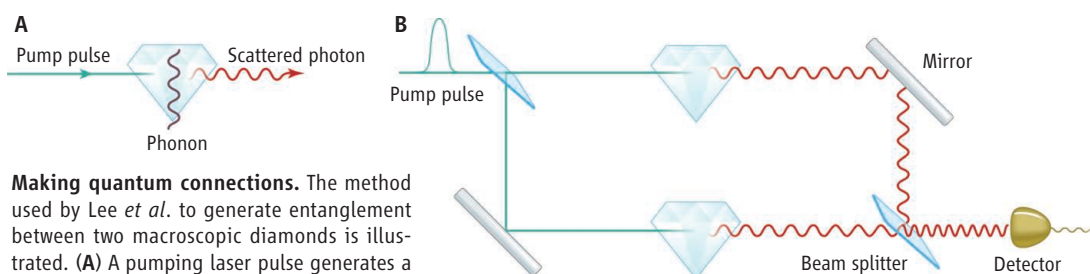


photon, it could have come from either of the diamond crystals in which one phonon was excited. The indistinguishability of these two possibilities during detection means that the two diamond samples coherently shared one phonon, which is the hallmark of a quantum-entangled state.

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



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.

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 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

1. K. C. Lee *et al.*, *Science* **334**, 1253 (2011).
2. L.-M. Duan, *Nature* **414**, 413 (2001).
3. C. W. Chou *et al.*, *Nature* **438**, 828 (2005).
4. T. Chanelière *et al.*, *Nature* **438**, 833 (2005).
5. N. Sangouard, C. Simon, H. de Riedmatten, N. Gisin, *Rev. Mod. Phys.* **83**, 33 (2011).
6. D. L. Moehring *et al.*, *Nature* **449**, 68 (2007).
7. S. Olmschenk *et al.*, *Science* **323**, 486 (2009).
8. E. Togan *et al.*, *Nature* **466**, 730 (2010).
9. C. Clausen *et al.*, *Nature* **469**, 508 (2011).
10. Supported by the National Basic Research Program of China (973 Program) 2011CBA00300 (2011CBA00302), Army Research Office, and Air Force Office of Scientific Research MURI program.

10.1126/science.1215444

ECOLOGY

Mathematical Dances with Wolves

Sebastian J. Schreiber

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.

Department of Evolution and Ecology, University of California, Davis, CA 95616, USA. E-mail: sschreiber@ucdavis.edu

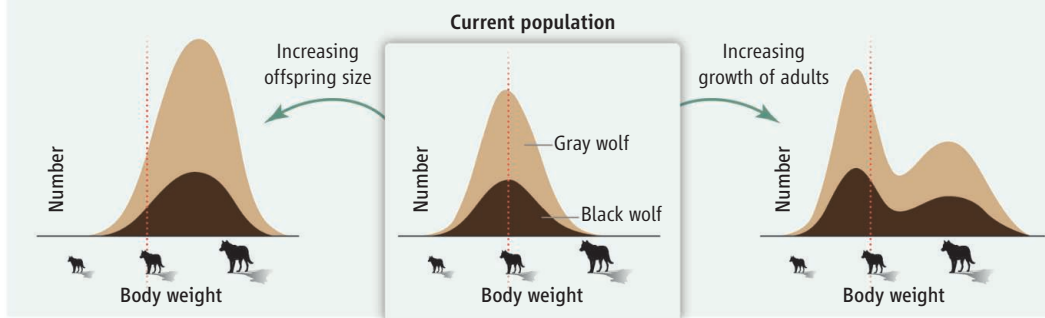
The 280 radio-collared wolves studied by Coulson *et al.* are direct descendants of 41 gray wolves reintroduced into Yellowstone National Park between 1995 and 1997 (4). This reintroduction was part of a larger effort involving a simultaneous reintroduction in Idaho and a naturally colonized population 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

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

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-



Complex predictions. Gray wolves in Yellowstone can have two different coat colors (black and gray). Coulson *et al.* use an integral projection model to explore how coat color and body size vary under environmental perturbation. Model predictions are consistent with several key features of the current Yellowstone population, including the population size, the frequency of black coats, and the mean body size. Environmental perturbations that increase either the mean body size of offspring or the growth of larger-sized individuals have different predicted long-term effects.

type-specific and the IPM dynamics include genetic laws of inheritance. The single-locus change determining coat color is particularly simple, but the IPM framework naturally extends to multilocus genetics.

By parameterizing the IPMs with the gray wolf data, Coulson *et al.* provide a tour-de-force demonstration of the forecasting power of IPMs. On the evolutionary side, the gray wolf IPM predicts that the prevalence of black-coated individuals in Yellowstone is maintained due to a fitness advantage of individuals with both the black allele and gray allele at the K locus. The source of this fitness advantage remains a mystery.

By perturbing vital rates in the IPMs, Coulson *et al.* illustrate the complexity of long-term ecological and evolutionary responses to environmental change (see the figure). For example, if an environmental perturbation increases offspring body size, then gray-coated individuals become more common, the variation in individual body sizes decreases, and selection for increased fertility becomes weaker. By contrast, if environmental perturbations increase adult growth rates, then gray coats become less common, the variation in individual body sizes increases (even becoming

bimodal), and the strength of fertility selection increases. Both perturbations result in larger population size and higher mean body size. These complex predictions highlight the need for data-driven models at the ecological-evolutionary interface.

Climate change models predict increased variation in environmental factors over the next century (11). How important is this increased variation relative to changes in the mean? Although the answer is likely to be species- and environment-specific, Coulson *et al.* illustrate how IPMs can tackle this question by separately varying the mean and temporal variation in vital rates. They find that changes in the mean have a larger impact on ecological and evolutionary dynamics. This result may stem from wolves being long-lived, averaging out the impacts of environmental fluctuations over their lifetime. Consistent with this view, a recent meta-analysis of matrix models for plant and animal populations suggests that short-lived species such as algae and insects are more strongly affected by increasing environmental variability than longer-lived species such as birds and ungulates (12).

The bewildering complexity of changes in wolf populations due to environmental

change may be disheartening at first glance. I am nevertheless optimistic that applying IPMs to more population data sets will identify how these complex responses depend on the demographic-genetic structure of populations and their environmental context.

Despite this optimism, many additional challenges remain. Although one can easily perturb vital rates in IPMs, Coulson *et al.* point out that it remains to be shown how environmental changes map onto changes in vital rates. Many effects of climate change on vital rates are likely to be indirect; for example, increasing temperature may affect plant availability for the wolf's prey. IPMs must therefore ultimately include species interactions. Such extensions could also provide insights into the cascading effects of gray wolf dynamics on other species (13) and identify counterintuitive indirect effects resulting from ecological and evolutionary feedbacks (14). Accounting for

these additional complexities and gathering data sets to constrain this complexity may be necessary to anticipate future ecological and evolutionary responses of populations to climate change.

References and Notes

1. C. Parmesan, *Annu. Rev. Ecol. Syst.* **37**, 637 (2006).
2. T. W. Schoener, *Science* **331**, 426 (2011).
3. T. Coulson *et al.*, *Science* **334**, 1275 (2011).
4. E. E. Bangs *et al.*, *Wildl. Soc. Bull.* **26**, 785 (1998).
5. U.S. Fish and Wildlife Service, Rocky Mountain Wolf Recovery 2010 Interagency Annual Report, www.fws.gov/mountain-prairie/species/mammals/wolf/annualrpt10/FINAL_2010_Northern_Rockies_Summary_and_Background_3_9_11.pdf (2010).
6. E. Randi, *Mammal Rev.* **41**, 99 (2011).
7. H. Caswell, *Matrix Population Models* (Sinauer, Sunderland, MA, 2001).
8. M. R. Easterling, S. P. Ellner, P. M. Dixon, *Ecology* **81**, 694 (2000).
9. S. P. Ellner, M. Rees, *Am. Nat.* **167**, 410 (2006).
10. T. M. Anderson *et al.*, *Science* **323**, 1339 (2009).
11. C. Tebaldi, K. Hayhoe, J. M. Arblaster, G. A. Meehl, *Clim. Change* **79**, 185 (2006).
12. W. F. Morris *et al.*, *Ecology* **89**, 19 (2008).
13. R. L. Beschta, W. J. Ripple, *Biol. Conserv.* **142**, 2401 (2009).
14. S. J. Schreiber, R. Bürger, D. I. Bolnick, *Ecology* **92**, 1582 (2011).
15. This work was facilitated by NSF grants EF-0928987 and DMS-1022639. I thank T. Schoener, J. Stachowicz, and the members of the DEEP lab for valuable feedback on an earlier draft.

10.1126/science.1214845

Mathematical Dances with Wolves

Sebastian J. Schreiber

Science, 334 (6060), • DOI: 10.1126/science.1214845

View the article online

<https://www.science.org/doi/10.1126/science.1214845>

Permissions

<https://www.science.org/help/reprints-and-permissions>

Use of this article is subject to the [Terms of service](#)