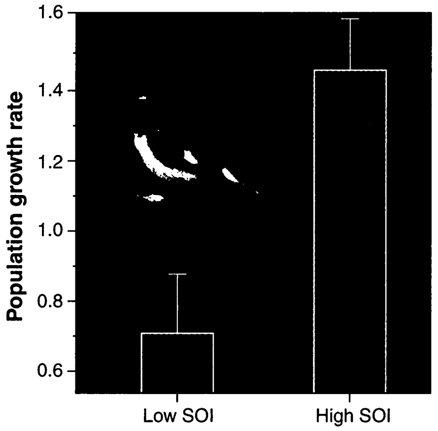


Fly away. The predicted population growth rate (mean ± SD) of the black-throated blue warbler, a migratory bird species, under El Niño conditions (low SOI; 1992 to 1994) and in three La Niña years (high SOI; 1988,1989, and 1996). Estimates of adult survival rates at the warbler's Jamaican wintering site have been combined with estimates of their reproductive rate at the New Hampshire breeding site (*4*). (It is assumed that the survival rate among juveniles is half the adult survival rate) (*10*).

scale climate changes affecting not only survival in southern wintering grounds but also reproductive performance in northern breeding areas.

The black-throated blue warbler is a migrant songbird that breeds in forests in eastern North America and winters primarily in the Greater Antilles (in the Caribbean). Sillett and co-workers took advantage of a long-term data set (1986 to 1998) from Hubbard Brook Experimental Forest in New Hampshire, USA (the warbler's breeding ground), and from northwest Jamaica in the West Indies (the warbler's winter quarters). With the Hubbard Brook data set they were able to show that the fecundity rate was lower under El Niño conditions than in La Niña years. They attributed this to an effect on the body mass of the fledglings, which is closely associated with the probability of first-year adult survival in many small songbird (passerine) species. Often the fecundity rate of small passerines is limited by food availability. Accordingly, Sillett *et al.* showed that, under El Niño conditions, there was a reduction in the biomass of lepidopteran larvae, the favorite food of the warbler. As a consequence, El Niño (with a low SOI value) resulted in a decrease in the number of new yearlings entering the New Hampshire population the following year.

With the Jamaica data set Sillett and colleagues were able to study the relation between ENSO and warbler winter survival. They noticed that there was a positive correlation between the number of juveniles in the study site in October and the SOI value, indicating that the pattern recorded in New Hampshire was not just a local phenomenon. Thus, in both study sites, low annual recruitment of first-year birds was related to El Niño conditions. The demographic consequences of El Niño years were further supported by a positive correlation between annual survival at the Jamaican wintering grounds and SOI.

The consequences of climate effects on animal population dynamics may be considerable. For example, consider predicting the warbler population growth rate by combining survival in the Jamaican study site with the reproductive rate at the breeding grounds in New Hampshire (see the figure). Assuming no effects of population density on population fluctuations, the population growth rate will be more than twice as high in La Niña years as in El Niño years (see the figure). Obviously, changes in the probability of an El Niño event (for example, because of the effects of global warming) are likely to strongly affect the population dynamics of this species (as predicted for other passerines) (*9*).

The Sillett *et al.* analysis provides another illustration of the need for detailed long-term studies to determine the many complex effects of global warming on animal populations.

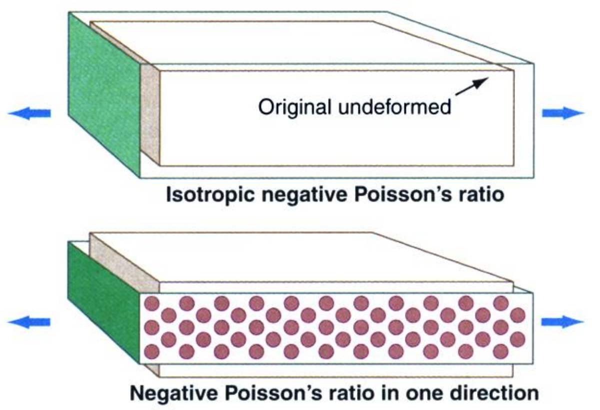
References
1. M. E. Mann *et al.*, *Geophys. Res. Lett.* **26**, 759 (1999).
2. Intergovernmental Panel on Climate Change, Climate Change 1995. *The Science of Climate Change* (Cambridge Univ. Press, Cambridge, 1996).
3. L. Hughes, *Trends Ecol. Evol.* **15**, 56 (2000).
4. T. S. Sillett, R. T. Holmes, T. W. Sherry, *Science* **288**, 2040 (2000).
5. R. C. Stone *et al.*, *Nature* **384**, 252 (1996).
6. C. S. Robbins *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **86**, 7658 (1989).
7. J. J. Den Held, *Ardea* **69**, 185 (1981).
8. W. Peach *et al.*, *Ibis* **133**, 300 (1991).
9. B.-E. Sæther *et al.*, *Science* **287**, 854 (2000).
10. T. W. Sherry and R. T. Holmes, in *Ecology and Management of Neotropical Migratory Birds*, T. E. Martin and D. M. Finch, Eds. (Oxford Univ. Press, Oxford, 1995), pp. 85–120.

PERSPECTIVES: MATERIALS SCIENCE

Deformations in Extreme Matter

Roderic Lakes

Most materials, when stretched, become narrower in cross section, as can be observed by stretching a rubber band or a piece of sponge rubber. This narrowing is represented by Poisson's ratio, ν, which is defined as the negative transverse strain of a stretched or compressed body divided by its longitudinal strain. For most solids (*1*), ν is between 0.25 and 0.33; for rubber, it approaches 0.5. Because it is easy to change the shape of rubbery materials (they have a small shear modulus) but much more difficult to change their volume (they have a much higher bulk modulus), they are called incompressible. On page 2018 of this issue, Baughman *et al.* (*2*) examine unusual lateral deformations in matter with cubic structure and reach the surprising conclusion that a negative Poisson's ratio may occur naturally in several forms of matter with extremely high or extremely low density.



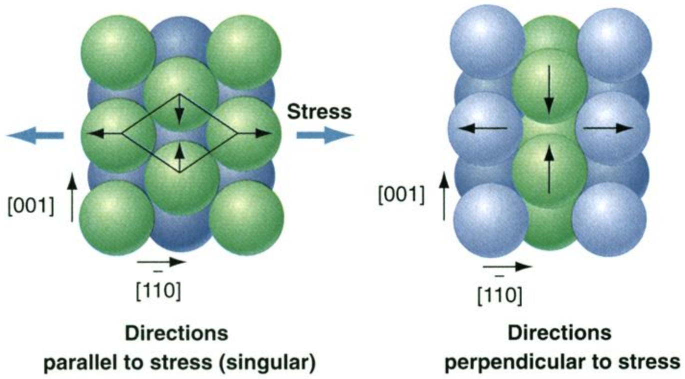
An unusual stretch. Stretching of materials with a negative Poisson's ratio causes an unexpected transverse expansion. This is unlike rubber and other common materials. If the material is isotropic, the expansion is in both transverse directions (**top**). Stretching cubic extreme matter can cause expansion in one direction and contraction in another direction at constant volume (**bottom**).

CREDIT: A. MORRIS/THE ACADEMY OF NATURAL SCIENCES

The limits for stability of an isotropic continuum (in which properties are independent of direction) suggest that ν can be between −1 and 0.5. The reason is that for the material to be stable, the bulk and shear stiffnesses (moduli) must be positive. These stiffnesses are interrelated by formulas that incorporate Poisson's ratio. Materials with a negative Poisson's ratio become fatter when stretched—a counterintuitive property (top panel in the first figure). For many years, negative

The author is in the Department of Engineering Physics, Engineering Mechanics Program, Biomedical Engineering Department, University of Wisconsin–Madison, 147 Engineering Research Building, 1500 Engineering Drive, Madison, WI 53706–1687, USA. E-mail: lakes@engr.wisc.edu

Poisson's ratios were unknown and even thought to be impossible (*3*). Since then, foams with ν as small as −0.8 have been produced by changing the shape of the cells (*4*). These foams expand laterally when stretched. Isotropic negative Poisson's ratio materials easily undergo volume changes but resist shape changes and may thus be viewed as the opposite of rubbery materials, or "antirubbers" (*5*).



Stretching a cubic crystal with negative Poisson's ratio. [001] refers to the direction along a cubic principal axis. [011] and [1$\bar{1}$0] are directions at a 45° angle from a cubic principal axis.

To achieve a negative Poisson's ratio, one must have noncentral forces or an unfolding mode of deformation (*6*, *7*). Milton has presented hierarchical laminates (*8*) that approach the isotropic lower limit $\nu \approx -1$ and called such materials "dilational" because they easily change volume. These laminates have a chevron structure with multiple length scales. Alderson and Evans have made microporous ultrahigh molecular weight polyethylene (*9*) with a negative Poisson's ratio by sintering and extrusion and called it "auxetic."

Anisotropic materials have properties that depend on direction. This extra freedom makes it easier to attain unusual or extreme behavior. For example, arsenic, antimony, and bismuth (*10*) are highly anisotropic in single-crystal form; Poisson's ratios calculated for these materials are negative in some directions (bottom panel in the first figure). A crystalline form of silicon dioxide, α-cristobalite (*11*), exhibits Poisson's ratios of +0.08 to −0.5, depending on direction. Many cubic metals when deformed in an oblique direction with respect to the cubic axes exhibit a negative Poisson's ratio (see the second figure) (*12*).

Anisotropy can give rise to curious effects. Remarkably, it is possible for Poisson's ratio to be negative in one direction and highly positive in another direction, so that the material becomes denser when stretched (*13*). Baughman *et al.* now show that the surprising combination of incompressibility and negative Poisson's ratio in a cubic material is also possible (*2*). These characteristics are incompatible in an isotropic material. Baughman *et al.* predict negative Poisson's ratios for several extreme forms of matter, such as ultradense matter (10^4 to 10^{11} g/cm^3) in neutron star crusts and white dwarf star cores. These "star crystals" are thought to have a body-centered cubic structure, similar to the structure of some metals. However, extreme matter is not held together by the same forces as metals. The particles in extreme matter interact by a Yukawa potential in which the usual 1/r Coulomb dependence decays exponentially. This can be due to charge screening. In contrast, bonding in metals can be approximated as a balance between the attraction between atom cores and repulsion from an electron gas. Similar counterintuitive behavior is also predicted in ultralow density (10^{-15} g/cm^3) plasma "crystals" of trapped ions and in colloidal crystals of particles in a liquid matrix. Plasma crystals were actually observed to have a negative Poisson's ratio (*2*).

Understanding of these unexpected properties of dense matter may help in understanding reaction rates and "star quakes" in dense stars. Tuning of the Poisson's ratio in low-density cubic plasmas could be useful in sensors or in photonic light valves. Besides providing an intriguing glimpse into the strange properties of some unusual materials, Baughman *et al.*'s results may therefore be of importance both in fundamental studies and for applications.

CREDIT: ADAPTED FROM (12)

References

1. S. P. Timoshenko and J. N. Goodier, *Theory of Elasticity* (McGraw-Hill, New York, ed. 3, 1970).
2. R. H. Baughman *et al.*, *Science* **288**, 2018 (2000).
3. F. P. Beer and E. R. Johnston, *Mechanics of Materials* (McGraw-Hill, New York, ed. 1, 1981, ed. 2, 1992).
4. R. S. Lakes, *Science* **235**, 1038 (1987).
5. J. Glieck, *New York Times*, 14 April 1987, Science Times, p. 21.
6. R. S. Lakes, *J. Mater. Sci.* **26**, 2287 (1991).
7. L. L. Rothenburg, A. A. Berlin, R. J. Bathurst, *Nature* **354**, 470 (1991).
8. G. Milton, *J. Mech. Phys. Solids* **40**, 1105 (1992).
9. K. L. Alderson and K. E. Evans, *Polymer* **33**, 4435 (1992).
10. D. J. Gunton and G. A. Saunders, *J. Mater. Sci.* **7**, 1061 (1972).
11. A. Y. Haeri, D. J. Weidner, J. B. Parise, *Science* **257**, 650 (1992).
12. R. H. Baughman, J. M. Shacklette, A. A. Zakhidov, S. Stafström, *Nature* **392**, 362 (1998).
13. R. H. Baughman and D. S. Galvao, *Nature* **365**, 735 (1993).

PERSPECTIVES: OCEANOGRAPHY

Tracer from the Sky

Michael L. Bender

The stable isotope abundance ratios of light elements such as hydrogen, carbon, and oxygen often vary slightly in materials at Earth's surface. These variations result from subtle differences in the chemical or physical behavior of atoms of the same element but different masses and can provide important information about geological, biological, climatic, and hydrological processes. On page 2028 of this issue, Luz and Barkan (*1*) exploit one such isotopic variation to determine the gross rate of photosynthesis in seawater.

The rate of marine photosynthesis is of great importance, because the process establishes the basis of the food chain, supports vertical carbon fluxes that induce nearly all chemical variability in the oceans, and affects climate by influencing the CO_2 concentration of surface seawater and, therefore, the concentration of CO_2 in air. It is difficult to measure from environmental properties because it does not directly induce substantial chemical changes (these are a manifestation of net production or photosynthesis in excess of respiration). It is also difficult to measure in vitro, because capturing an ecosystem "in a bottle" may change its characteristics and does not provide a means of adequately covering the oceans.

The work of Luz and Barkan is based on the anomalous isotope composition of O_2 in air, perhaps the smallest and most obscure isotope abundance variation discovered to date. Oxygen has three stable isotopes, ^{16}O (99.76%), ^{17}O (0.04%), and ^{18}O (0.20%). Isotope abundance variations generally depend on mass, and variations in $\delta^{17}O$ (the difference in parts per thousand in $^{17}O/^{16}O$ ratios between a sample and a standard) (*2*) are normally 0.5 (actually 0.52) times as large as those in $\delta^{18}O$. But the $\delta^{17}O$ of O_2 in air is about 0.2 per mil (‰) less than 0.52

The author is in the Department of Geosciences, Princeton University, Princeton, NJ 08540, USA. E-mail: bender@princeton.edu