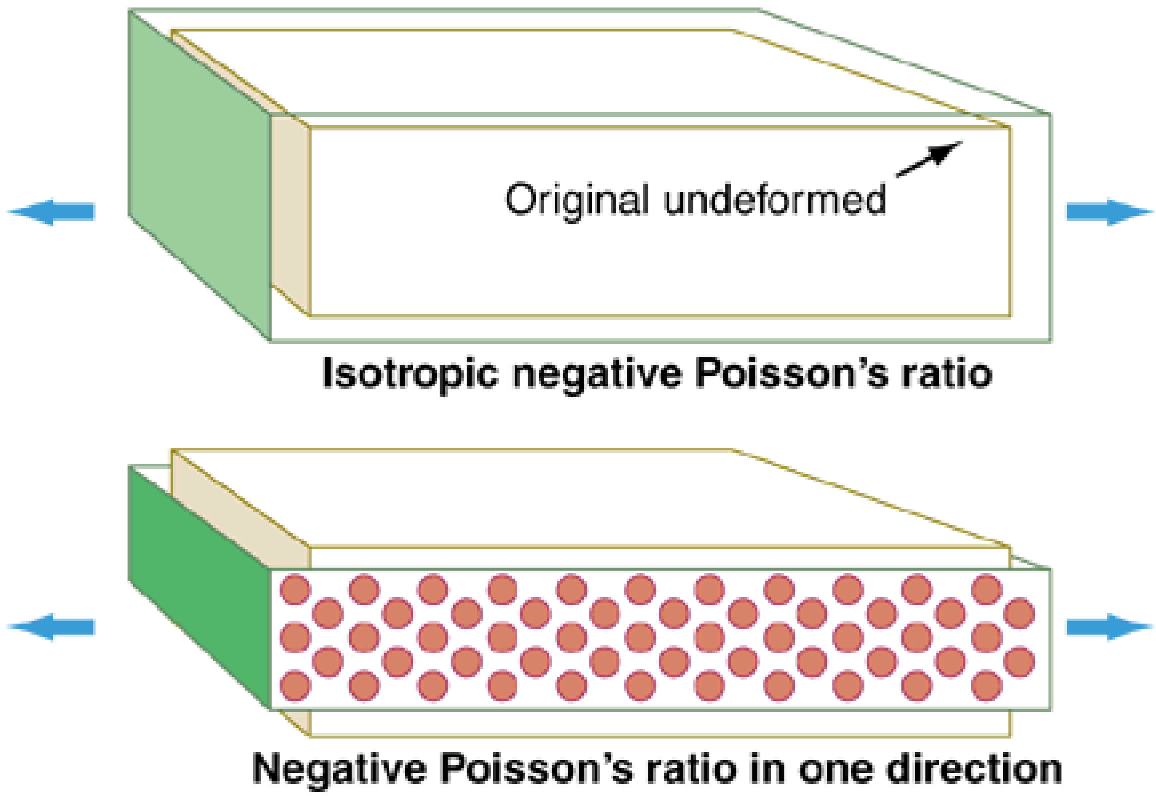
PERSPECTIVES: MECHANICAL PROPERTIES

Lateral Deformations in Extreme Matter

adapted from

Lakes, R. S., "Lateral Deformations in Extreme Matter", *Science*, 288, 1976, June (2000).

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.

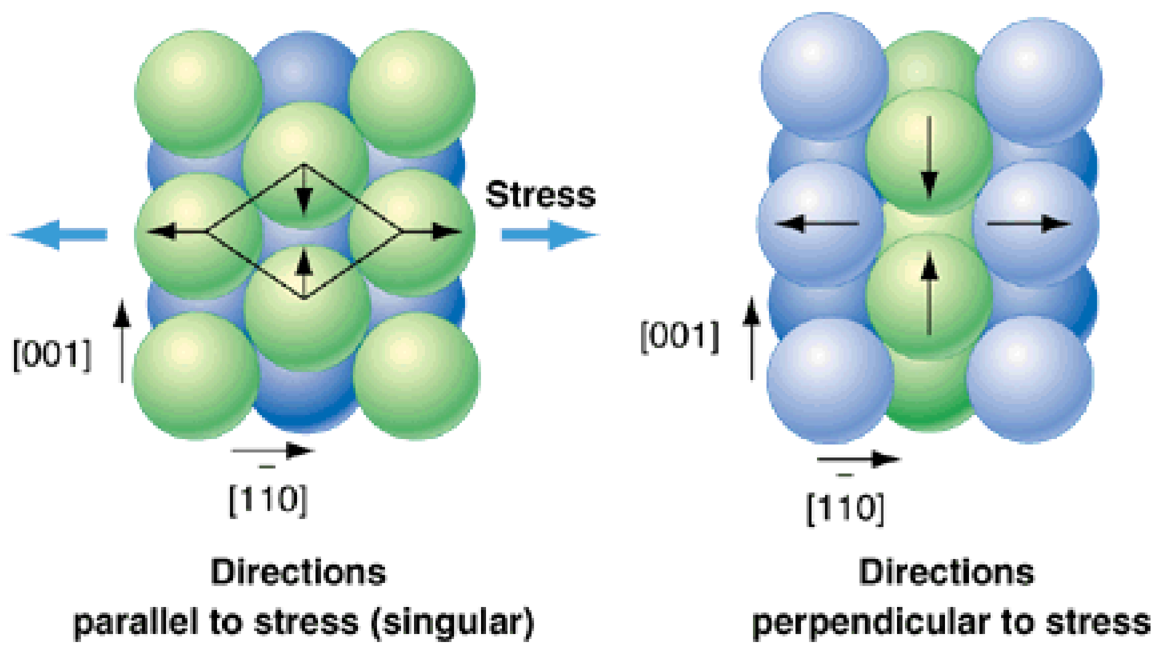


An unusual stretch. Stretching of materials with a negative Poisson's ratio causes an unexpected transverse expansion. This is unlike rubber and other common materials. If the material is isotropic, the expansion is in both transverse directions (top). Stretching cubic extreme matter can cause expansion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

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 Poisson's ratios were unknown and even thought to be impossible (3). Since then, foams with n 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).

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."

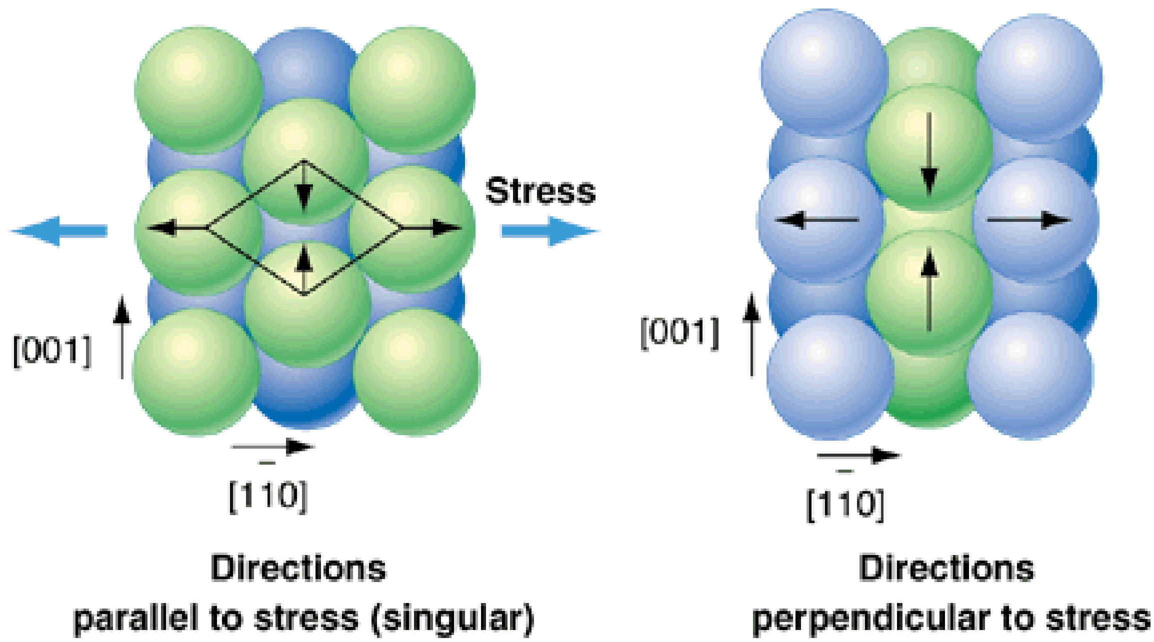
Anisotropic materials have properties that depend on direction. This extra freedom makes it easier to attain unusual or extreme behavior. For example, arsenic, antimony, and bismuth (10) are highly anisotropic in single-crystal form; Poisson's ratios calculated for these materials are negative in some 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)



Stretching a cubic crystal with negative Poisson's ratio. [001] refers to the direction along a cubic principal axis. [011] and [1¯10] are directions at a 45° angle from a cubic principal axis.
CREDIT: ADAPTED FROM (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.



Stretching a cubic crystal with negative Poisson's ratio. [001] refers to the direction along a cubic principal axis. [011] and [1¯10] are directions at a 45° angle from a cubic principal axis.
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) [publisher's information].
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).

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