Avoiding the shrink

Auxetic materials

Materials that expand laterally when stretched can act as molecular-scale strain amplifiers. This amplification might be exploited in nature and in future technologies.

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When compressed in a vice, the sides of a material are expected to bulge. Conversely, stretching is expected to make a material thinner — as for the rubber band on your desk. Most materials exhibit these dimensional changes in lateral directions to decrease the volume change produced by the applied strain. But materials do exist that expand in at least one lateral direction when stretched. Known as auxetic materials, they have recently gone from being rarely recognized to appearing rather commonplace. In fact, much of the crystalline matter in the Universe may be in auxetic phases, from most cubic phases of metals to super-dense crystals thought to comprise the outer crust of neutron stars and the cores of white dwarfes. These auxetic materials exist across an enormous range of conditions — from near absolute zero and densities of approximately 10^{-15} g cm^{-3} for plasma ion crystals to above 10^{6} K and densities of 10^{11} g cm^{-3} for proposed crystals in stars.

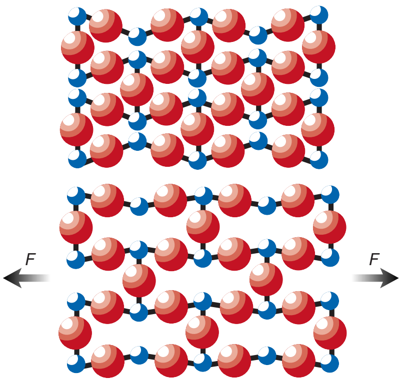
The Poisson ratio (defined as −1 times the ratio of lateral to applied elastic strains) describes the behaviour of stretched materials — positive Poisson ratios characterize the expected normal behaviour, whereas auxetic materials have a negative value. Although Poisson's ratio for cubic phases must be between −1 and +2, there is no theoretical limitation on this ratio for materials with less internal symmetry. Although few crystals have negative Poisson's ratios for all stretch and lateral directions, such behaviour can be obtained for foams of most materials.

The behaviour of some auxetic materials seems more fitting for Alice's Wonderland than for the real world. After an initial elongation, stretching the porous polytetrafluoroethylene used as artificial arteries generates up to an 11-fold higher relative expansion in one lateral direction. Although the direct effect of a negative Poisson's ratio is to cause an expansion that decreases density during stretching, a small fraction of auxetic crystals actually increase in density when stretched. This behaviour is quite rare, but all 13 observed stretch-densified crystals (out of 500 investigated crystals) are auxetic.

The answer to this paradox is that very large positive Poisson's ratios are made thermodynamically possible by the existence of negative Poisson's ratios. Indeed, cubic metals that have the most positive Poisson's ratio for one lateral direction also have the most negative Poisson's ratio for the second lateral direction. One origin of this association between negative and positive Poisson's ratios is illustrated in the picture. Applying a force F elongates the sheet by causing bond angle changes at the blue atoms, which produces a large lateral expansion (corresponding to a negative Poisson's ratio) and opening of void space in the sheet. Neighbouring sheets of atoms, above and below a central sheet, can then move closer to partially occupy this void space — thereby increasing the density of the material (corresponding to a positive Poisson's ratio).

Auxetic materials could be used as strain amplifiers if the strain-amplification factor (−1 times the Poisson's ratio) is larger in magnitude than one. Strain amplification close to the maximum Poisson's ratio of +2 occurs for cubic phases, and even this small amplification could be useful. However, auxetic materials with lower symmetry can have giant strain amplification factors, for example porous polytetrafluoroethylene has a Poisson's ratio of up to −12, which is about 40 times larger than that for most materials. Amplification of the effect of hydrostatic pressure on a linear dimension is possible for the small fraction of auxetic crystals that are stretch densified, as these crystals also must have a negative linear compressibility — and a linear compressibility can exceed the volumetric compressibility if a linear compressibility is negative. In fact, a linear compressibility of auxetic lanthanum niobate crystals in one direction is 9.6 times greater than its average linear compressibility. Likewise, stretching (or compressing) a known auxetic polymer produces over a tenfold larger magnitude volumetric strain.

There are various possible applications of these amplification effects. A slab of auxetic material could replace cumbersome lever systems currently used for amplification, which degrade frequency response, thereby amplifying an actuator-generated strain by over an order of magnitude. As the structural elements providing auxetic behaviour can have molecular dimensions, auxetic materials could be used in molecular-scale amplifiers. Large negative linear compressibilities — the required inverse effect to stretch densification — might find application for interferometric optical pressure sensors, where pressure-induced increases in both a dimension and density could avoid the usual partial cancellation of phase shifts due to changes in the refractive index and physical path length. Optical lenses piezoelectrically driven to provide very large changes in refractive index also seem achievable, as refractive index is sensitive to volume and a tensile strain can produce a ten times larger volumetric strain.



Stretching some rare types of auxetic materials surprisingly makes them denser.

Such mechanical amplification associated with auxetic materials might explain why cell growth and metabolism are affected by minute pressures of approximately 10 kPa, such as those experienced when biological organisms are submerged in a metre of water. For example, lipid bilayers have been observed to increase in thickness when hydrostatically compressed (signifying a negative linear compressibility and stretch densification), and a negative Poisson's ratio has been calculated for membranes found in the cytoskeleton of red blood cells. As phase stability requires that the sum of all linear compressibilities for any material is positive, a material with a negative linear compressibility must be incompressible in certain directions (between directions of positive and negative linear compressibilities). Use of this feature might help marine animals preserve dimensions key for biological functions while travelling to the depths of the ocean. ■

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FURTHER READING

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