The sizes of the refocused spots are shown in panel e. Even though the two antennas were just λ/30 apart, the signals returned to each antenna. Neighboring antennas receive little spillover.

Sending flowers

Despite running their experiment 100 times and obtaining the same result, the Paris researchers remained skeptical of their superresolution. To convince himself and his colleagues, Lerosey proposed a second test: Separate a color image into its red, green, and blue components. If the superresolution is real, three closely spaced antennas should be able to transmit and receive the encoded red, green, and blue images without spillover. Recombining the refocused images should yield the original image in full color. But if the superresolution is spurious, the three antennas will receive the same loosely focused signal; the image will be in black and white.

As figure 1 shows, Lerosey's test succeeded and vindicated not only Fink's Green function explanation but also an equivalent theoretical treatment. In 2000 Rémi Carminati of École Centrale Paris and his collaborators analyzed the time-reversal symmetry of fields containing evanescent components.[2] Using Werner Heisenberg's *S*-matrix approach, they showed that scatterers placed in the near field can, in effect, convert an evanescent wave into a propagating wave.

Time reversal isn't the only new path to superresolution. So-called metamaterials that have negative indices of refraction can bend light so strongly that an image is produced in the near field. A second lens or probe can transfer the image into the far field for readout.

Fink argues that metamaterials have an inherent drawback. In focusing beyond the diffraction limit, waves pass through the metamaterial. So far, negative refraction is achievable only for single wavelengths and in a highly anisotropic way.

Time reversal, on the other hand, achieves superresolution not through refraction but through a mathematical operation akin to reflection. What the TRM and antennas are made from doesn't impair their focusing ability. Fink hopes soon to apply his time-reversal technique to the production of images.

Charles Day

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A novel composite is stiffer than diamond

A crystal form that is unstable in isolation can be confined in tin to yield a material with unprecedented resistance to compression or extension.

The genius of hot and sour soup is that two very different culinary ingredients—chili oil and vinegar—unite to give a distinct flavor, piquant and tangy. Engineers who devise recipes for composite materials apply a similar principle. They might combine a strong material resistant to breakage with a stiff material resistant to deformation and fabricate a composite that is both strong and stiff. But just as hot and sour soup prepared with an ounce of chili–vinegar mixture is not as spicy or sour as it would be were it prepared with an ounce of either undiluted ingredient, one might expect that the engineer's composite is not as strong as its strongest constituent nor as stiff as its stiffest. A rigorous theorem confirms that intuition.[1]

But in 2001, Roderic Lakes of the University of Wisconsin–Madison and colleagues created a material with a stiffness greater than theoretically allowed. They did it by violating the assumptions of the stiffness-bounding theorem. Specifically, they fabricated composites with *negative*-stiffness inclusions. Now, six years later, Lakes's group has reported on a material whose stiffness, at least over a small temperature range, is greater than that of steel, tungsten carbide, and even diamond.[2]

Freedom from movement

Three-dimensional materials can be deformed in various ways, and they are characterized by more than one kind of stiffness. The phenomenal stiffness observed by Lakes and company was an elastic stiffness, a resistance to compression or extension. Very stiff materials, says Lakes, are useful in fabricating devices such as computer disks, whose dimensional tolerances have to be very tight.

Elastic stiffness is often quantified by Young's modulus. Consider a bar, and apply a compressing pressure to its ends. The bar will get slightly shorter until it exerts a force balancing the externally applied pressure. Young's modulus is the pressure divided by the fractional change in the length of the bar.

Springs offer 1D models for thinking about negative stiffness and the physics behind Lakes and colleagues' observation. An ideal spring's stiffness is quantified by the Hooke's law constant k; for a negative-stiffness spring, k is negative. Such a spring would be unstable. If you attach a mass and extend the spring just a tad beyond its equilibrium length, you'll see it continue to expand. The spring is likewise unstable to minute compressions.

Although the negative-stiffness spring is unstable in isolation, it can be part of a stable system if conventional springs with sufficiently large positive k are attached to each of its ends and if the displacement at the boundary of the three-spring system is specified. (The 1D system is subtly different from real 3D materials, for which one can fix either the displacement or the force acting on the boundary and still have stability.) Figure 1 illustrates the idea and also shows how a negative-stiffness inclusion can contribute to a system with very high stiffness.

In Lakes and company's composite, a tin matrix plays the role of the conventional springs. The negative stiffness is realized by a particular crystal form of barium titanate.

At high temperature, $BaTiO_3$ has a cubic unit cell and resists compression and extension as does a conventional spring. The material undergoes a phase transition at about 120 °C to a form with a tetragonal unit cell. In principle, the phase transition could leave the $BaTiO_3$ in an unstable equilibrium configuration analogous to the negative-stiffness spring. But tetragonal $BaTiO_3$, more complicated than a 1D Hooke's law spring, also has available a stable equilibrium form. A real-world cubic-to-tetragonal phase transition carried out on isolated $BaTiO_3$ produces the stable form.

In the Wisconsin group's protocol, small bits of $BaTiO_3$ are added to molten Sn, which then cools. In time, the $BaTiO_3$ undergoes the cubic-to-tetragonal phase transformation, but now confined in a Sn matrix. Lakes and company reasoned that, like the surrounding springs in figure 1, the Sn matrix might be able to stabilize the

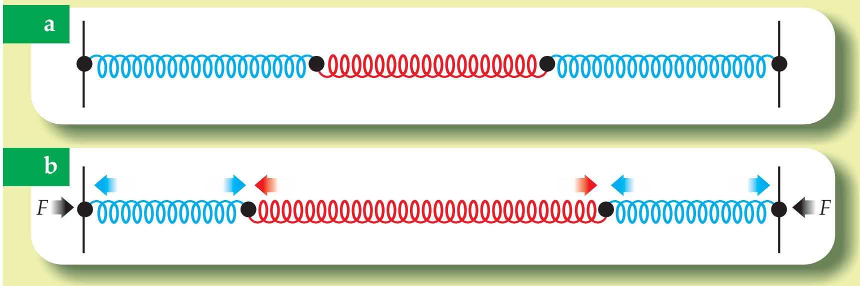

Figure 1. A negative-stiffness spring (red) can be stabilized by surrounding it with conventional springs (blue). **(a)** Three equal-length springs are at their equilibrium lengths. If the displacement of the system's boundary (outer black dots) is specified and the magnitude of the spring constant for the conventional springs is at least twice that of the negative-stiffness spring, the system is stable for small displacements of the two internal masses (black dots). **(b)** The system is subject to an external compressing force *F*. With an expanded central negative-stiffness spring, external and internal forces can be in balance even though the total system length doesn't change.

$BaTiO_3$. That is, confined in the matrix, $BaTiO_3$ might exist in the tetragonal form that would be unstable in isolation. The result is a composite with negative-stiffness inclusions.

Figure 2 shows a micrograph of an extreme-stiffness specimen. The $BaTiO_3$ accounts for a relatively small 10% of the volume. To determine Young's moduli of their samples, Lakes and colleagues subjected them to a bending force applied at 100 Hz. The periodic application allowed the group to explore the lag, expressed as a phase offset, between force and sample response.

Bending may seem to be quite different from the linear compression or extension that defines Young's modulus, but when an object bends, some of it compresses while other parts expand. Thus, the degree to which a specimen bends encodes Young's modulus. To determine that bending, Lakes and colleagues measured the angular shift of laser light reflecting off the sample. Recognizing that the phase-transition temperatures of $BaTiO_3$ confined by Sn and $BaTiO_3$ in isolation could be quite different, the researchers also monitored specimen temperature through several heating and cooling cycles.

Most of the Wisconsin team's composites exhibited an anomalous stiffness incompatible with having only positive-stiffness components. Figure 3 presents data for one of the minority of samples whose Young's moduli exceeded that of diamond. Several features are noteworthy. First, the specimen's behavior changes significantly from one temperature cycle to the next. Lakes suggests that the detailed microstructure of the inclusion–tin interfaces is key to determining a composite's stiffness. That so-far uncontrollable quality varies from sample to sample and changes with thermal cycling.

Second is that the diamond-surpassing stiffness exists only over a small temperature range. Third, the phase offset is negative in that region of extraordinary stiffness. According to Lakes, the negative phase shift indicates an internal release of potential energy, perhaps a consequence of inclusions rolling down their potential-energy hills away from the unstable equilibrium. "We think the inclusions expand," he says. "But that's an inference; we haven't actually measured the expansion."

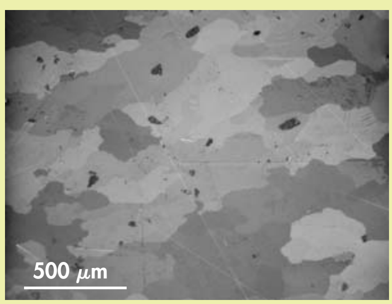

Figure 2. Inclusions of barium titanate in a tin matrix can yield extremely stiff composites. In this micrograph, taken with polarized light, the $BaTiO_3$ inclusions are black and the Sn appears as varying shades of gray. (Adapted from T. Jaglinski et al., ref. 2.)

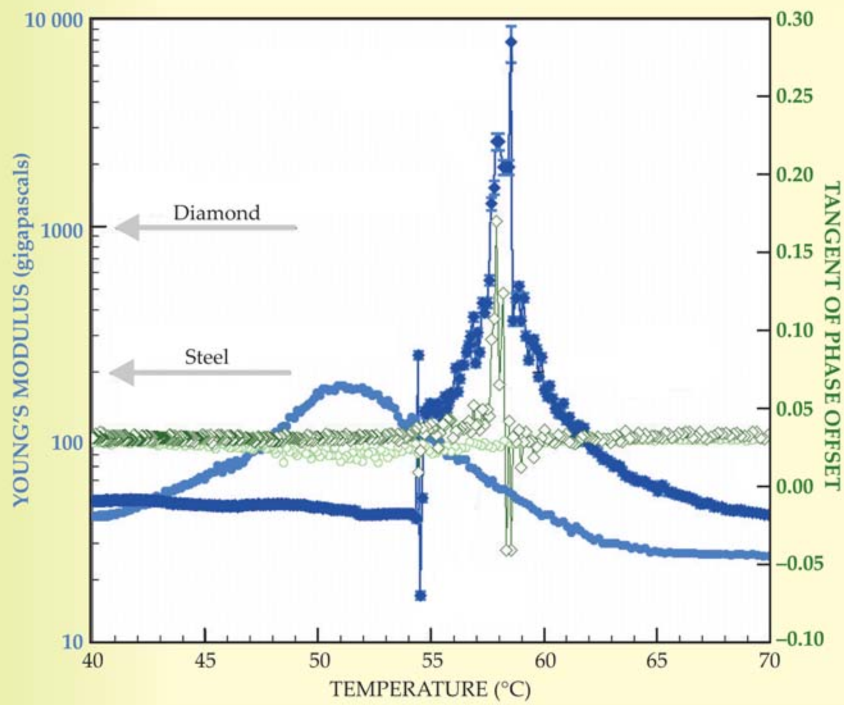

Figure 3. Young's modulus of composites with barium titanate inclusions can have a magnitude greatly exceeding that of diamond. The plot shows the modulus (blue) and phase offset (green) for two temperature passes—one indicated by lighter colors and circular data points, the other by darker colors and diamond-shaped data points. (Adapted from T. Jaglinski et al., ref. 2.)

Almost simultaneously with the Lakes and company paper, Walter Drugan, a University of Wisconsin colleague and collaborator of Lakes's, published a theoretical demonstration that static 3D composites with negative-stiffness elements can be stable.[3] Drugan's consideration of static systems is important: The extreme stiffness evidenced in figure 3 is a transient effect that occurs during a dynamic temperature scan. Sometimes, notes Drugan, systems can be stabilized by dynamic processes. But if super-stiff composites are to see practical applications, they will need to be stable under static conditions.

In future work, Lakes hopes to expand the temperature range over which his composites exhibit extreme stiffness. One idea that he and Drugan have considered proceeds from the ability of a little bit of negative-stiffness inclusion to have a whopping effect on composite stiffness. Thus, it might be possible to fabricate a composite with small quantities of distinct materials, each of which undergoes a phase transition at a different temperature to a stabilizable negative-stiffness form. Over a wide range of temperatures, the composite could exhibit remarkable stiffness, with the several inclusions taking their turn in being responsible for the surprising effect.

Steven K. Blau

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Mechanical force may determine the final size of tissues

By assuming compression inhibits cell division, two independent simulations account for the growth and size of a simple model organ.

Even before a fly egg first divides, the structural changes that culminate in an adult fly begin. The body's two major axes emerge first, followed, in the embryo, by the appearance of compartments that will become the mouth, legs, and other organs of the eventual maggot.

Those structural milestones, and later ones in the life cycles of flies and other organisms, are controlled by signaling molecules called morphogens. Since the 1970s biologists have identified numerous morphogens in their favorite fly, *Drosophila melanogaster*. The morphogens' often whimsical names, like wingless and hedgehog, describe deformities that befall the fly when the corresponding genes mutate.

Although their underlying biochemistry is complex, the ability of morphogens to pattern tissue and trigger growth appears to be a straightforward consequence of the response they evoke in cells and of their spatial distribution and transport properties. What's harder to understand is how—or whether—morphogens determine a growing tissue's final, correct size.

To grapple with that question, developmental biologists work with fly tissues called imaginal disks. Those simple sheets of epithelial cells form in the heads of maggots. By the time the maggot has become an imago (its first adult stage), the disks resemble the wings and other organs they'll eventually become. The disks of *D. melanogaster* are not especially easy to work with. They are small and don't grow in vitro. But those disadvantages are offset by the preexisting trove of data gathered on the fly's anatomy, physiology, and genetics.

Viewed under a microscope, the imaginal disk cells appear to divide and grow at a rate that depends only weakly on their location in the tissue. What tells them to stop? The question is all the more puzzling because, as the image on the cover shows, morphogen concentration varies strongly across the disk.

Two years ago Boris Shraiman of the Kavli Institute for Theoretical Physics in Santa Barbara, California, asked himself what could prevent the cell division rate from following the morphogen profile. His answer, in a theoretical paper published two years ago, is mechanical feedback.[1] Shraiman hypothesized that mechanical stress affects cell growth and proliferation through an as-yet unidentified molecular mechanism. In particular, compression acts as a growth inhibitor.