A Protective Cloak Against Earthquakes and Storms

Invisibility cloaking is not close on the horizon, but shielding from other types of damaging waves may be more feasible.

Gregory J. Gbur

Almost a decade ago, the first scientific research on optical invisibility cloaking was unveiled, but in spite of a furious amount of theoretical and experimental effort, there are still numerous obstacles to overcome before a Klingon or Harry Potter-style cloaking device comes even close to reality. Indeed, serious theoretical limitations indicate that such devices may not ever be possible, even in principle.

An ideal cloak guides waves around a central region, much like water flowing around a boulder in a stream, and objects in this region will not "see" the waves at all. This property actually is a disadvantage for an invisibility cloak—the wearer of the cloak won't be seen, but also won't be able to see anything. But there are other types of waves than light, and attempts to apply the ideas of cloaking to protect objects or people from the damaging effects of water, sound, magnetic, or even seismic waves suggest that the technology may play an important practical role in science and engineering after all. In fact, the use of cloaking devices for protection, rather than hiding, may be the greatest application that comes out of the still quite young discovery.

Invisible Roots

The roots of invisibility in physics start with a very different sort of protective technology altogether. In the early 1970s, British engineer Sir Godfrey Hounsfield developed the first three-dimensional medical imaging technique, the now-ubiquitous computed axial tomography (CAT) scan, and demonstrated its safe and effective use in imaging the brain. In CAT, the object to be studied is exposed to X-rays from multiple directions, producing a set of individual images that are combined via computer to form a complete three-dimensional picture of the object.

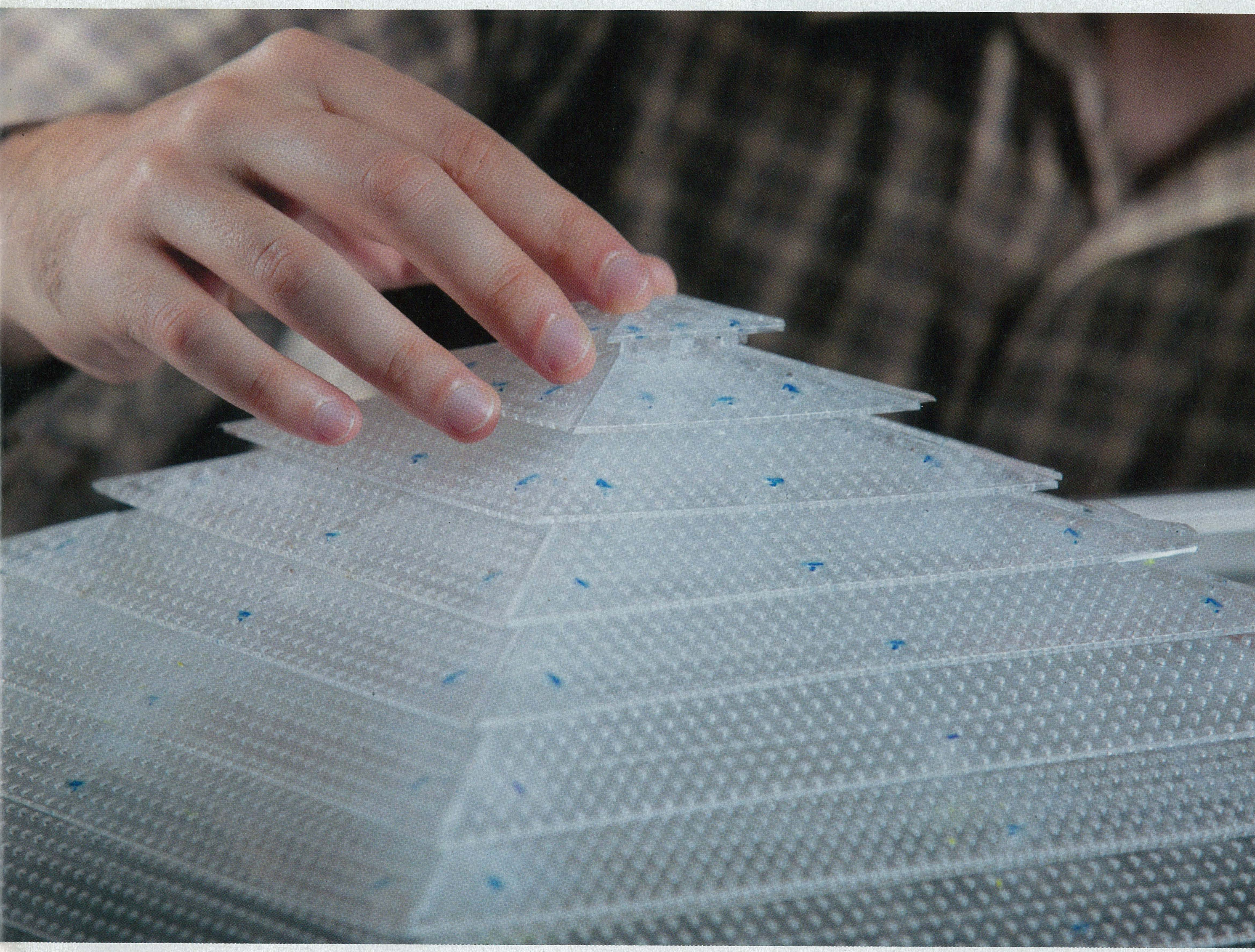
X-rays, however, are relatively ineffective at resolving soft tissue. Researchers thus began to develop new medical imaging techniques using other types of waves, but an immediate concern arose: What if some objects can't be seen using these new techniques? In other words, is it possible for some objects to be invisible to an imaging technology? If "invisible tumors," for instance, are possible, then any technique that uses waves to probe the human body could have huge, literally fatal, flaws.

Fortunately, theoretical work in the late 1980s demonstrated that, in general, invisible objects do not exist. It turns out that it is possible for an object to be perfectly invisible when illuminated from a single direction—for instance, many people have walked into unseen glass doors when the lighting is just right—but it was seemingly impossible to have an object invisible for all directions of illumination.

This result seemed to settle the matter until 2006, when a pair of theoretical papers appeared in the journal *Science*. Both papers produced theoretical designs for invisibility cloaks using a new technique called *transformation optics*. When light passes from one material to another, such as from water to air, it changes direction in a process called *refraction*. This effect is evident when looking at a straw in a glass of water: The straw appears to have a kink in it at the interface between the water's surface and the air above. The key to transformation optics was the observation that bending light waves, in many cases, is mathematically analogous to warping space. By first designing the desired warping, in this case the bending of light around a cloaked region, one can reverse-engineer the type of materials needed to make the cloaking device.

How could cloaking devices possibly exist, when earlier research had seemingly proven invisibility to be impossible? The authors of the papers came up with different resolutions of this seeming contradiction. Ulf Leonhardt, now at the Weizmann Institute of Science in Israel, simply noted that the nonexistence of "perfect" invisibility does not exclude the possibility of near-perfect invisibility: An object that is 99 percent invisible, for instance, would likely be acceptable for most practical applications. However, the authors of the second paper, working at Imperial College and Duke University, noted that the original nonexistence proofs did not account for certain extremely specialized materials that are not found in nature but could, in principle, be constructed in a laboratory. Such materials are now known as *metamaterials*. Whereas most materials in nature respond only to the electric field in visible light, metamaterials could be designed with a magnetic response as well. Furthermore, most natural materials are isotropic, meaning that light propagates at the same speed in the material regardless of what direction it is traveling. Anisotro-

Gregory J. Gbur is an associate professor in the department of physics and optical science at the University of North Carolina in Charlotte. He received his PhD in theoretical physics from the University of Rochester in 2001. He is currently investigating new theoretical techniques to design directional and multidirectional optical cloaks, as well as the connection between invisibility and media that possess both gain and loss. He blogs at http://skullsinthestars.com. E-mail: gjgbur@uncc.edu.



The purpose of this acoustic cloaking device is to return sound waves to a listener as if nothing were there to alter them. The researchers performed a long series of calculations to determine the precise placement of the holes and plastic sheets that would alter the reflected waves' trajectories to match those from a flat surface. The technology could potentially be used for underwater sonar cloaking, or to adjust acoustics in concert halls. (Photograph courtesy of Pratt School of Engineering, Duke University.)

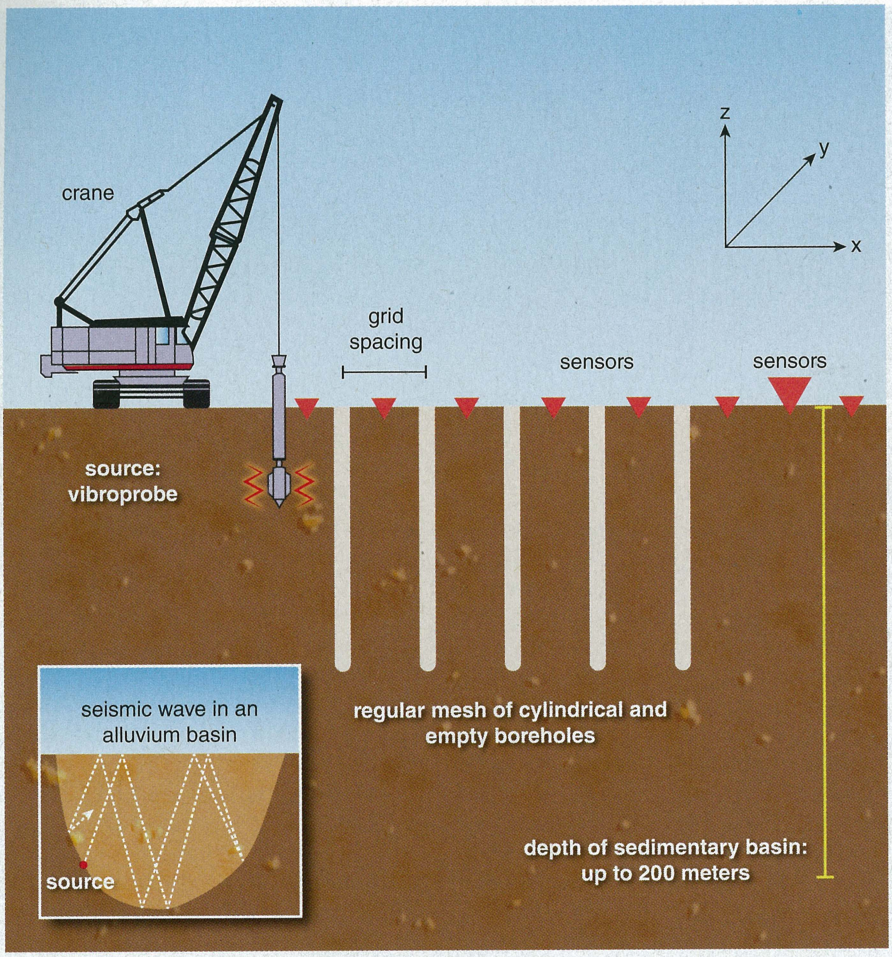
pic metamaterials, in which the speed of light depends on direction, also provide additional freedom to design true cloaking devices.

In late 2006, the Imperial College–Duke University team built and tested a crude but functioning cloaking device that could shield an object from microwave radiation. Since that time, a variety of different cloaking designs have been proposed, and a number of them have been tested. The Duke team reported in 2014 on a setup that cloaks against acoustic waves. Although none of the devices can even remotely claim to be truly invisible, they illustrate that the theoretical concepts are sound.

However, true cloaking faces a number of major obstacles. On the practical side, the construction of metamaterials requires the ability to manipulate the structure of matter on a scale smaller than the wavelength of light. As visible light has a wavelength on the order of a millionth of a meter, this task is not yet within our practical capabilities. An even more daunting challenge is on the theoretical side. In order for the cloak to be truly undetectable, light must travel through the inside of the cloak in the same amount of time it takes light to travel past the cloak on the outside. However, the light inside the cloak must travel a longer distance in order to avoid the cloaked region, which means it must travel faster than outside light. The speed of light in air is almost identical to the vacuum speed of light, so light inside the cloak must travel faster than that. It is possible to achieve this feat for a very small range of frequencies without violating Einstein's relativity, but it does not seem to be possible for the entire visible spectrum at once. In other words, one might be able to cloak for a certain shade of red, but the object would be highly visible for every other color of light.

Disaster Shields

Although perfect, or even reasonably good, optical cloaking may never be achieved, many of the difficulties in cloaking for visible light are not present for other types of waves. There is no fundamental upper limit on the speed of such waves, and the wavelengths involved are much longer



The basic idea behind seismic cloaking is to alter the density of the medium, causing the waves to change speed and, by extension, direction, so they go around a target. A recent experiment demonstrated that a series of precisely spaced bore holes could effectively change the direction through the ground of vibrational waves produced by an artificial source. (Adapted from Brûlé et al., 2014.)

than those of light, making them easier to manipulate. If we are interested in designing cloaks to protect against damaging waves, we do not even need to chase perfection. A cloaking device that reduces the impact of an earthquake hitting a building by even one magnitude might make the difference between the building standing or falling.

A cloaking device that reduces the impact of an earthquake hitting a building by even one magnitude might make the difference between the building standing or falling.

Several setups using cloaking ideas to protect against waves have been proposed. A building could be surrounded by an arrangement of carefully placed holes or pillars embedded in the ground, effectively changing the density of the ground and thereby altering the direction of destructive seismic waves around the structure. (It is an interesting legal question, however, to ask what would happen if the waves then hit the next building in line.) Remarkably, the basic idea was tested in 2013 by researchers from Aix-Marseille Université in Marseille, France. An array of subsurface holes was designed to shield from an artificial seismic-wave generator (*see figure at left*). Although the system simply blocked waves rather than guided them, it successfully demonstrated that subsurface structures could do the job.

Cloaking from sound waves in air or water is also possible; in 2011 researchers at the University of Illinois at Urbana-Champaign demonstrated experimentally a cloaking device that could protect against underwater ultrasound waves. They used 16 concentric rings made of connected cavities, each of which was designed to alter sound speed differently, thus guiding the waves around the center.

Another intriguing possibility is protecting against damaging ocean waves. In 2012, Mohammad-Reza Alam of the University of California, Berkeley, proposed a novel type of cloaking device for such an application. It takes advantage of the presence of subsurface disturbances called *interfacial waves* that commonly arise in the ocean at a depth where the temperature, and thus the density, of water changes drastically. By putting a patterned structure on the seafloor around a buoy or offshore platform, it is theoretically possible to convert the surface waves approaching the structure into subsurface waves that pass harmlessly underneath; on the other side of the structure, those waves would then be returned to the surface. As yet, no experiments have been done to test this idea.

Alternate Paths

Waves don't have to be the only target for such technology. In 2012, researchers from Aix-Marseille Université and Ecole Centrale Paris introduced the idea of a thermal cloak, which can shield a region from heat flux. In essence, the cloak provides a "path of least resistance" for the heat to follow, so that it tends to travel around the outside of the cloaked region before penetrating the center. In the end, it is impossible to prevent heat from eventually reaching the middle, but such a design could provide additional insulation for heat-sensitive devices, such as electronics.

Another possible area of protection is from magnetic fields. Also in 2012, a research collaboration between Slovakia and Spain experimentally demonstrated a magnetic cloak, consisting of a superconducting ring, which pushes away magnetic fields, and an iron ring, which pulls magnetic fields in. Together, the nested rings guide magnetic fields around their interior. This magnetic cloaking technique could prove useful in medical imaging. In magnetic resonance imaging, a powerful magnetic field forms the imaging signal, and is so strong that most of the electronics running the device must be kept in a completely different room. A magnetic cloak for these electronics could allow the devices to be smaller and less expensive.

It is even possible to create a cloak for electrical currents. In 2012, researchers at Lanzhou University and Southeast University in China experimentally demonstrated a direct-current electric invisibility cloak. Such a cloak could give new freedom to electrical engineers in how they design circuit geometries without causing interference between components.

Another approach to optical invisibility is to record the background scene and then project it onto an obstructing object, in this case the retroreflective garment worn by the person above. The illusion works only from a limited set of viewing angles. This method is not strictly cloaking, as the light waves are not guided around an object, but it has some similar potential protective uses, such as allowing drivers to see through blind spots in their vehicles. (Photograph courtesy of Tachi Laboratory, University of Tokyo.)

Transformation optics techniques also may be able to camouflage, in essence creating a "cloak" that can make any object look like any other object. Researchers at the Hong Kong University of Science and Technology first theoretically demonstrated this idea in 2009, and a number of variations have been explored in the years following. These researchers created an illusion of a hole in a wall, effectively making an opaque surface see-through. Conversely, the same researchers also demonstrated that it is possible to make an object appear to be much bigger than it actually is. Such an illusion could be used, for instance, to make a wide-open secret door appear to be simply another section of solid wall. None of these possibilities, however, have been demonstrated yet for walls or doors thicker than a millionth of a meter.

Limited forms of invisibility can provide protection in quite unexpected ways. In 2003, even before the first theoretical cloaking papers appeared, a literal cloak of a different sort was introduced by Susumu Tachi at the University of Tokyo. In this case, a camera records the scene behind the cloak and projects it onto the retroreflective garment, making the wearer appear perfectly transparent from a limited set of viewing angles. This prototype was not designed as a fashion accessory, but as a demonstration of a technology that could be used to make the interior of a car or an airplane see-through. A pilot or driver could then, virtually, see everything around them at all times and be aware of dangers that would traditionally be completely out of sight. In 2014, a University of Rochester team carefully arranged a series of lenses to create a small zone of invisibility, which they say could have similar uses, or even allow surgeons to see through their own hands during a procedure.

A cloak has traditionally been a garment that travelers wear to protect themselves against harmful weather. The proposed applications of invisibility physics show that science may yet be able to provide similar cloaks against almost anything nature has to offer.

Bibliography

Brûlé, S., E. H. Javelaud, S. Enoch, and S. Guenneau. 2014. Experiments on seismic metamaterials: Molding surface waves. *Physical Review Letters* 112:133901.

Gbur, G. 2015. Designing directional cloaks from localized fields. *Optics Letters* 40:986–989.

Kim, S-H., and M. P. Das. 2012. Seismic waveguide of metamaterials. *Modern Physics Letters B* 26:1250105.

Landy, N., and D. R. Smith. 2013. A full-parameter unidirectional metamaterial cloak for microwaves. *Nature Materials* 12:25–28.

Leonhardt, U. 2006. Optical conformal mapping. *Science* 312:1777–1780.

Norris, A. N., and W. J. Parnell. 2012. Hyperelastic cloaking theory: Transformation elasticity with pre-stressed solids. *Proceedings of the Royal Society A* 468:2881–2903.

Parnell, W. J. 2012. Nonlinear pre-stress for cloaking from antiplane elastic waves. *Proceedings of the Royal Society A* 468:563–580.

Pendry, J. B., D. Schurig, and D. R. Smith. 2006. Controlling electromagnetic fields. *Science* 312:1780–1782.

For relevant Web links, consult this issue of *American Scientist Online:*

http://www.americanscientist.org/issues/id.116/past.aspx