In race to make things disappear, scientists gain ground on science fiction

By Charles Petit • Photo illustration by Cary Wolinsky and Rick Kyle

If Leonardt is riding high these days, with a new award from the Royal Society of Great Britain to further develop his ideas on how to make things in plain sight disappear...

Born in East Germany and now occupying the theoretical physics chair at Scotland's University of St. Andrews, Leonardt is among the leaders of the worldwide race to realize an old dream of science fiction: cloaking devices. They would steer light or other electromagnetic waves around them like water around a stone in a smooth stream, leaving nary a ripple of difference in the flow. Such things, letting light swing past like a thrown object, would be invisible.

Cloaking devices are a common term in technical literature. It also deludes evokes myth and popular fiction. Allusions include the Romanian technology that first amazedistle viewers of the old Star Trek in the episode "Balance of Terror," when hostile Bird of Prey fighting vessels just disappeared, poof... One finds cloaking in J.R. Rowling's novels about the young wizard Harry Potter with his invisibility cape... Farther back, H.G. Wells' novel *The Invisible Man* (and the movie of the same name, along with its sequel *The Invisible Woman*) lacked the same idea...

J.B. Tolkien assigned similar power to The One Ring to his tales of hobbits. Inspiration for the ring apparently came from way back - the shield of the Gorgon recovered from an earthquake-spawned chasm in Plato's *The Republic*.

Leonardt's role in the cloaking field's rise to respectability didn't get off to an encouraging start. The details of his initial frustration and eventual triumph illustrate the subtleties with which the field entered the mainstream - even surprising some experts. "I began my work at a time when invisibility was not fashionable at all," he says. That was about a decade ago. After years of quiet work with a few colleagues, he wrote a paper titled "Optical conformal mapping." The abstract's first words come right to the point: An invisibility device should guide light around an object as if nothing were there."

In 2005 he sent the paper to Nature, which rejected it, and to *Nature Physics*. Editors at *Nature Physics*, Leonardt recalls, took just two days to reject the paper as well. So, he says, he sent it to Science. There, it lasted two weeks before it was rejected. In early 2006 he tried again, this time with *Physical Review Letters*, or *PRL*. Another no-go. One reviewer said the mathematics, while classical (the calculations refer to Maxwell's and Newton's equations of light and to other mathematical constructs credited to such names as Fermat, Lagrange, Euler, Descartes, Euclid, Kepler, Einstein and Feynman), did not offer enough new physics. Ouch.

But it was another *PRL* reviewer's rebuttal that opened Leonardt's eyes wide. It said he was not alone. The assessment, routinely shared with Leonardt, indicated that the reviewer had been to two meetings in the previous month in which John Pendry discussed his group's efforts on the same topic, calling it a cloaking device. In the November 2006 meeting in Los Angeles, *PRL* had offered to publish the work.

Pendry's group was led by his former doctoral student Alexander Zakharian. Pendry and his colleagues, the assessment added, "subsequently have filed a patent related to this work." Hence, the anonymous reviewer declared, the work was no new and did not merit publication in *PRL*.

It came as a surprise to Leonardt that he had been in unwitting competition with Pendry, one of the most distinguished scientists in Britain. Pendry is a visiting professor of theoretical physics at Imperial College London - he is Sir John. The queen knighted him in 2004 for his services to science. Much of his reputation is based upon achievements in optical theory and metamaterials that refract light in a fashion - even backward - not found in natural substances. Leonardt was pleased to have a rival of such eminence but furious over his paper's treatment. Because Pendry's team had not published its work, Leonardt argued in a letter to *PRL*, the journal...
**FEATURE | INVISIBILITY UNCLOAKED**

Conventional refractive material

Metamaterial

Typical behavior: When light waves hit an object, they are reflected (top), allowing the object to be seen. Transmittant materials also refract, or bend, light (bottom). The amount of bending depends on a property called the refractive index. Because air has a lower index than water, refraction causes a saw to look split when it enters a glass of water. But conventional materials don't bend light in a way useful for cloak. 

Negative refraction: Conventional materials have refractive indices greater than 1, meaning they bend light toward a vacuum. But some materials exhibit negative refraction, meaning they can make light bend backward on itself. This could lead to a stepper that seems to defy reality (illustrated), but also offers cloaking possibilities. Ordinarily designed metamaterials (diagonal, left) can steer light around a solid object.

A metamaterial cloak (outer ring) steers light.

People have jumped onto the theme, and how successful they have been. There are some wonderful ideas out there," says Leonard. "It has gotten more interesting than I expected. The theoretical sides of the field was over very quickly. Now it is being turned into reality.

A few examples:

- Xiang Zhang of the University of California, Berkeley, and the Lawrence Berkeley National Laboratory says he and a few others in the field have their eyes on a cloakable material that can work at visible wavelengths—but it's a secret for now, so he can't say what it is. "You could trip on it, and feel it, but you wouldn't see it," he predicts. The secret recipe needs more work, he says, and ought to be ready for publication in a year... or more.

- At Purdue University in West Lafayette, Ind., physicist Vladimir Shalaev is pretty sure he can do it, too, and is happy to describe the material (basically, mirrors and air), but he isn't sure how to shape it for practical use.

- Physicist Michal Lipson of Cornell University and her group have demonstrated a microscopic "carpet cloak," a miniature flat, reflective surface with a hump in it to hide the goods. The lump part looks as flat as the rest of the "rug," the team reports in the August Nature Photonics. Zhang's Berkeley 1016 report, led by grad student Jason Valentine, did the same thing, reporting the results in the July Nature Materials. "It's like we ripped a hole in the fabric of space," Valentine says. "Light wasn't going through it."

- This year in PRL, a team led by Che Ting Chua, a Berkeley-trained physicist at the Hong Kong University of Science and Technology, describes an approach called "remote cloak." It not only (in theory) renders an object invisible, but also does so with a differenting light to the other around the thing to be hidden. Invisibility, says one of the team's papers, is merely the process of altering the light so an object "looks like air." Even better, the group calculates, it might be possible to make one object look like another—for example "change an apple optically to [a] banana." The researchers call this what is offshoot "illusion optics."

Some of these methods work only within a narrow range of wavelengths, often in flat, two-dimensional settings. It's difficult to find anybody who thinks there will ever be a device that hides itself and its contents at all wavelengths—if you can't see it in the visible light, then perhaps infrared, radar, ultraviolet or X-rays would reveal it. But optimism for practical use is growing. So are the sources of money to propel research. In the United States, the National Science Foundation program officer Robert Trew says that the main division supporting such work—"Electrical, Communications and Cyber Systems—has about $10 million worth of contracts now out, shared among 16 researchers. But the researchers agree on one thing: Progress has been fast. "The field has amazed me," Pendry says.

Some researchers believe the halo effect could mislead some readers of the scoop, who might think it is a breakthrough in invisibility. "I don't think it's a breakthrough," says Pendry. "It's more like a trick. But I think it's a step towards making invisibility a reality."

**A hidie-hole in stretched space**

While cloaking is the term that has caught the public's eye, the broader field is known as transformation optics. Its power comes from a remarkable property of Maxwell's classic equations describing the behavior of light and other electromagnetic radiation. The equations are invariant, meaning that they work the same in different coordinate systems. Thus physicists can keep track of how light will behave if a real object is mathematically warped into something shaped quite different—or, vice versa. A dimensionless point in one mathematical realm, unaffected by passing light waves, can be expanded into a 3-D void in another coordinate system. But light or other radiation remains oblivious to the void.

Leonard, in his seminal paper in Science, described this as conformal mapping. Just as a mapmaker drops the geographic points on the Earth's globe onto a flat sheet—such as for a Mercator projection—mathematicians can map, or conform, the surface of one object onto something else. And Maxwell's equations remain unchanged.

Pendry, in a review in the July 10 Nature, explained the concept clearly: "Imagining that the optical system in question... is embedded in a rubber medium. We then stretch and pull the rubber, taking with it all the rays of light passing... until the rays are traveling in the desired directions." The same transformations that "stretched the rubber" also describe how the
collapsed star in deep space would (SN: 10/9/04, p. 10). All such seeming trickery is born of the same underlying optical sleights of hand. On the physics website arXiv.org, more than 30 papers have appeared in the past year with variants of "cloak" or "cloaking" in their titles. So for the devices have all been tests of the concept, with nothing close to practical. Furthermore, the small gadgets don't yet cloak anything perfectly, or cloak anything very large. Some regions have been made invisible are hard to see without a microscope. And because cloaks that shift longer wavelengths of light are easier to make, first successes came with microwaves—whose radiation can be measured in inches. Some devices work in the infrared with pinhead-sized or smaller wavelengths, with even shorter light waves just now showing up on the agenda.

Leonard and Pendry remain in the thick of it—and remain rivals. Each is eager to humiliate the other. The more of the other takes more than his fair share of credit for coaxing invisibility from obscurity.

While Pendry says Leonard's first published paper "had a good scheme," he adds that Leonard makes more of it than he should. "If it is not being straightforward, for his was not a full cloak, but an approximation"—because his approach did not have a full treatment of light as waves but handled it as a collection of rays. Leonard in turns says of Pendry, "He has done very important work, but he has not done everything. In particular the connection of this research area to general relativity, that's what we have done... He makes the impression that this whole field is due to him, and he used results that I developed without referencing them."

Sharp elbows are uncommon in highly competitive, new fields of science. But the researchers agree on one thing: Progress has been fast. "The field has amazed me," Pendry says.

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newly made cloak's properties must change—how its refractive index and permittivity must be altered—to permit Maxwell's equations to meet themselves as desired and steer the waves around the hiding place.

It is for this reason that papers on cloaking are often cluttered with the symbols ε and μ. These are epsilon and mu, the electrical permittivity and the magnetic permeability of a material. The values describe the way a substance resists the oscillating electrical and magnetic fields of electromagnetic radiation. Changes in these values can make light slow down, speed up and thus reflect, or bend. (Wave fronts reverse when one portion slows compared with the others.) While other qualities determine how transparent a material is to a given wavelength, ε and μ work pretty much the same all wavelengths. They are the components of the refractive index.

And metamaterials, whose refractive index can be engineered for more flexibility than can natural substances (even to the point of a negative index that bends light more than halfway back on its original direction), are the medium of choice.

Unlike the atoms and molecules that nature provides, which are limited in the combinations of electrical and magnetic permeability and permittivity, the novel metamaterials can mix and match ε and μ to provide exactly the radical refractive index variations that make light do loop-de-loops around a cloaked void.

Visible results The microwave cloak designed by David Smith's team (roughly shaped, bottom right; listen light's path just as the team expected (top right)) defies the changes in the electric field (color in both images at right) as the wave fronts move through the cloak and recombine on the other side. Notice how the cloak hides and diverts waves directly surrounding it.

Because light travels at a constant speed, the cloaked object is enclosed in a roundabout, cloaking void. The cloaking device distorts the wavefronts, allowing them to pass around the object without interference. This is demonstrated in the images above, where the wavefronts are shown in different colors. The bottom image shows the wavefronts after they have passed through the cloaking device, while the top image shows the wavefronts before they enter the device.

Beneath the rug Xi Zhang of UC Berkeley and colleagues have designed a cloak made of nanocrystalline silicon that can hide objects from view in the infrared. Light hitting an object normally scatters, giving way to the object's presence (left). But with the new "carpet cloak" (right), the light reflects as if it were bouncing off a flat surface (right). The cloak hid an area that measured 3.6 millimeters by 460 nanometers.

friendly to electric fields. The holes and pegs simply change the material's gross density, hence its electrical responses. "But it works, and that's a start." And it works at a broad range of infrared wavelengths, from about 1,000 to 1,800 nanometers.

The scheme will not work, however, at visible wavelengths, which range from 700 down to 400 nanometers, at least not with any fabrication method clear to the researchers. And wavelengths shorter than that—from ultraviolet to X-rays and below—remain pure science fiction for now.

As a result, these researchers have developed a cloaking device that uses metamaterials to bend light around objects. This is demonstrated in the images above, where the wavefronts are shown in different colors. The bottom image shows the wavefronts after they have passed through the cloaking device, while the top image shows the wavefronts before they enter the device.

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Explore more
- John Pendry on metamaterials and relativistic: www.smith.ph.ic.ac.uk/photonics/NewPhotonics/research.html
- UII Leonard's discussion of invisibility: www.st-andrews.ac.uk/~vli/invisibility.html
- Charles Petit is a freelance writer based in Berkeley, Calif.

www.sciencenews.org
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