HOW TO MAKE ANYTHING Disapp

From invisibility cloaks to optical computers, engineers are turning the laws of physics upside down.

BY **FRED HAPGOOD**

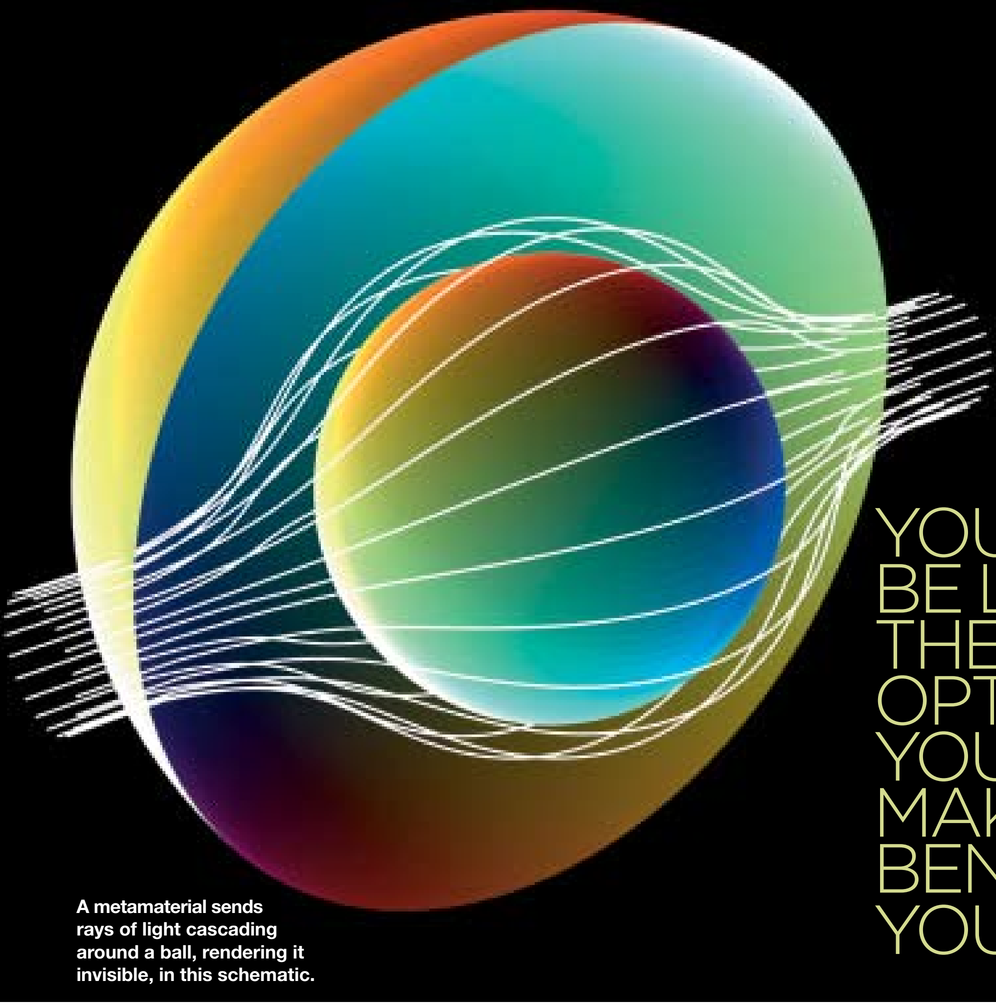
Xiang Zhang remembers the day he recognized that something extraordinary was happening around him. It was in 2000, at a workshop organized by DARPA (the Defense Advanced Research Projects Agency) to explore a tantalizing idea: that radical new kinds of engineered materials might enable us to extend our control over matter in seemingly magical ways.

The goal at hand, changing how objects interact with light, seemed at first blush to be routine; people had been manipulating visible light with mirrors and lenses and prisms nearly forever. But Zhang, a materials scientist then at the University of California at Los Angeles, knew those applications were limited. Based overwhelmingly on a single material, glass, the technologies were restricted by the laws of optics described in standard physics texts. The engineers in the room hoped to smash through those barriers with materials and technologies never conceived of before. The proposals included crafting what amounts to an array of billions of tiny relays; in essence, the relays would capture light and send it back out. Depending on the specific design of the array, the light would be bent, reflected, or skewed in different ways.

What could you do with a tool like that? An amazing amount, Zhang soon discovered. For one thing, you could render objects invisible. You see something, after all, when light bounces off it, creating the reflections that enter your eye and form an image on your retina. If you could direct light to flow smoothly around the object like water flowing past a

PHOTOGRAPH **BY BILL JACOBSON**


pear



A metamaterial sends rays of light cascading around a ball, rendering it invisible, in this schematic.

YOU WOULDN'T BE LIMITED BY THE LAWS OF OPTICS SINCE YOU COULD MAKE LIGHT BEND ANY WAY YOU LIKED.

rock in a stream, there would be no reflection, no rays entering your eye, and nothing to see—not even a shadow.

Harry Potter's invisibility cloak inevitably arises as an example of the power of such materials, but invisibility is just the start. Every tool based on the interaction of electromagnetic waves with objects, from modems and MRIs to radios and radar, could have their powers extended, altered, enhanced.

One version of the technology might lead to superfast optical computers, which store and process information using light. Another version might obliterate the line between the large things we can see and the small things we cannot. Instead of an invisibility cloak, imagine the reverse: a supermicroscope that would let you view vanishingly small objects such as individual strands of DNA. Such a tool could turbocharge biological research, advance computer chip manufacture, revolutionize education, and usher in an age of near-magical nanotechnology. The potential is so vast that Zhang and his colleagues have struggled for ways to sum it up.

The laws of refraction, which govern how light bends, were codified by the great Arab physicist Ibn Sahl in A.D. 984 and updated by the Dutch mathematician Willebrord Snellius in 1621. For almost four centuries these laws had been passed down from generation to generation unquestioned, like the laws of gravity. Suddenly it seemed possible to Zhang that you could stretch the law of refraction to its limits because you could make light bend in any direction you liked—including the exact opposite of the way glass and every other natural material bends it.

It was like learning that you could make a form of water that flowed uphill. Thomas Zentgraf, who works in Zhang's new lab at the University of California at Berkeley, puts it this way: "Imagine that you were raised in a world in which the only color was red. Then one day someone discovers blue."

At that DARPA conference, Zhang was only beginning to appreciate the hues and tints and shades. He realized the magnitude of the coming change when, during one conference session, a Defense Department scientist handed him a copy of an article. The man's eyes were dancing, and he had a broad smile. "Take a look at this," he said. Zhang started reading the paper, written by a professor in Hong Kong who was pursuing similar research but with a twist: Instead of light, he was working with acoustics. Sound is a kind of wave totally different from light, yet the principles were the same. In a flash Zhang saw that the concepts swirling around him were basic, universal new rules about how humans could control and manipulate the world. Right then he knew how he would be spending the next several years of his life.

"It was a very exciting moment," he says, with a scientist's penchant for understatement.

That moment was the culmination of the iconoclastic work of John Pendry, a physicist from Imperial College London. Back in the 1990s, Pendry, an expert in condensed-matter physics with a special interest in electromagnetism, was consulting with Marconi Materials Technology. The British company manufactured a radiation-absorbing carbon material that could hide battleships from radar detection but didn't know the physics of how it worked. Could Pendry find out?

Pendry discovered that the electrical properties allowing the

DAVID SCHURIG

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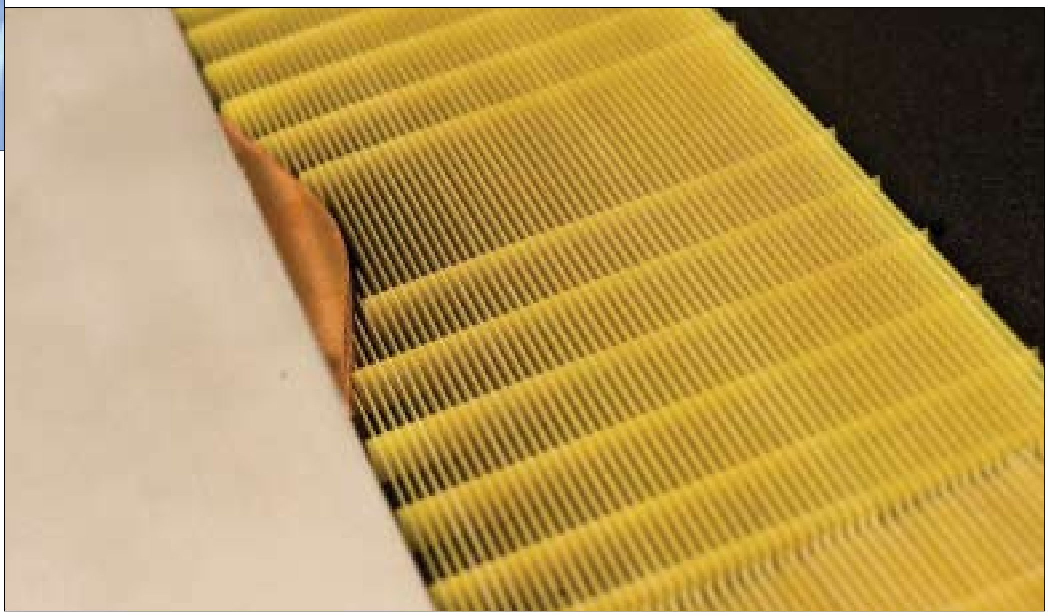

Above: John Pendry of Imperial College London. Right: A prototype invisibility device created by David Smith’s team at Duke. When microwaves shine through the meshlike metamaterial onto the copper-colored bump at center, the waves reflect back as if the bump were not there.

material to absorb radiation came not from the carbon per se but from the shape of its long, thin fibers.

Scientists had long known that they could change the behavior of a material by altering its chemistry. For instance, you can alter the color and hardness of glass by adding lead. But now Pendry saw that he could also alter function by changing a material’s internal structure on a very fine scale, less than a wavelength of whatever he was manipulating. (A wave of visible light, just about the size of a virus, has a length of a few hundred nanometers.)

These new, structurally altered materials would soon become known as metamaterials, based on the Greek *meta,* meaning “beyond.” “We knew we were onto something,” Pendry says.

Marconi was so pleased with Pendry’s insight into the carbon fibers that the company wanted to know whether he might have any new tricks up his sleeve. Pendry proposed trying to change the magnetic properties of a material. He wondered: Could he take a material that wasn’t intrinsically magnetic and magnetize it by altering its physical structure alone?

Ordinarily, either a material has the innate ability to be magnetized—generating forces from electrons moving inside them—or it does not. To invest this quality where it does not naturally appear, Pendry envisioned a theoretical metamaterial: a precisely crafted composite material that could selectively mimic properties of a conventional magnetic substance like iron. “Magnetism involves charge going around in a circle,” Pendry says. “If electrons in atoms could do this, then we could do it on a larger scale.”

This kind of metamaterial, he hypothesized, could be manufactured from minuscule loops of copper wire (copper is not naturally magnetic) embedded in a material like fiberglass. Pendry predicted that when current flowed through those loops, a magnetic response would occur.

There were many nuances to this scheme. If you cut the loops you could make a magnetic resonator, which would act like a switch. The switch would allow Pendry to change the magnetic properties of the fabricated material on command.

Pendry knew he was in uncharted territory, but at first he didn’t comprehend the magnitude of his idea: By combining the electrical properties of Marconi’s radar-absorbing material with the magnetism imparted by the copper wire, he had unknowingly figured out how to manipulate electromagnetic radiation, including visible light—making wild applications like Harry Potter’s invisibility cloak suddenly within reach.

Pendry’s incredible conception, published in a respected physics journal in 1999, stoked the imagination of scientists worldwide. One of the first to be drawn in was an experimental physicist at the University of California at San Diego named David Smith, who heard Pendry speak shortly before his landmark paper was published. Pendry’s results were startling, especially to a physicist, because magnetism is one of the core properties of matter. For any given element, this property or its absence was carved into atoms since the time of creation. The idea of being

IMPERIAL COLLEGE LONDON/MIKE FINN-KELCEY; DUKE PHOTOGRAPHY able to switch magnetism on and off was counterintuitive, to say the least. After the lecture, Smith returned to his lab and excitedly described to a colleague, Willie Padilla, what he had just heard. Padilla was just as captivated.

Smith and Padilla were the perfect sorts of scientists to hear Pendry's claim. Most of the physics one reads about in the popular press concerns big-picture concepts like string theory and black holes and alternate universes. Such matters are important, of course, but the profession has a lower-profile side as well: developing the skills and tools required to actually measure the behaviors of the physical world. The researchers who do this are called experimental physicists, and their guiding principle is that while the world is full of bright ideas, the only way to know if you have something real is if you can build it and then measure what you have built. Smith and Padilla belonged to this group.

Being who they were, they set to work immediately to build a real version of Pendry's device and measure its behavior. The magnetism switch built by Smith and Padilla was faithful, in concept, to the machine Pendry had conceived. Made of tiny structures, arrays of very small coils, it could "tune in" to a magnetic field the same way a radio antenna receives and concentrates signals of a given radio frequency. When illuminated by a source of radiation, the material behaved as though it were naturally magnetic.

By the time the pair's work was published, in May 2000, it was obvious that the ideas in play were far bigger than just artificial magnetism. A whole new branch of physics was coming up over the horizon. "We realized it was like finding a new state of matter no one had achieved before," Padilla recalls, still marveling. He, too, was beginning to think it might be possible to create a new class of materials, comprising substances whose physical properties came not from their position in the periodic table of elements but from design decisions made by human beings.

In a stroke of great luck, Padilla and Smith made their discoveries just as physicist Valerie Browning, a new DARPA program manager, was launching an initiative of her own. Better software, massive computational resources, and increasingly precise microfabrication techniques were making it possible to fabricate materials out of minuscule building blocks specifically engineered to exploit the different sorts of physics that emerge on very small scales. (To give one example, surface-to-volume ratios, which are critical to many physical behaviors, change radically with scale. To give another example, the rules of quantum physics—the physics that dominates inside the atom—give particles capabilities amazingly different from those we see in the macro world, from tunneling through solids to instant communication between particles that are located far apart.)

At first Browning called these hypothesized materials engineered composites. Later she called them metamaterials, the term Pendry and Smith used for their devices that interacted with waves. No matter what the name, the important thing was that, like Zhang, Browning envisioned the transformative power of this brave new material world. Even before Pendry published his breakthrough paper and before Zhang fathomed invisibility cloaks or computers of light, Browning was struggling to convince the military to fund a program based on her ideas about metamaterials. In 2000, with Pendry's paper vindicating her argument, she finally convinced DARPA to pony up $40 million for an advanced materials program. The agency was ready and waiting with an open checkbook when Smith and Padilla and Zhang, racing to build the new materials, sent proposals her way. With the money and motivation coming together, innovation soon followed.

By the fall of 2000, Pendry had laid the groundwork for a supermicroscope capable of seeing to a scale never before achieved. The inability to see the extremely small is becoming more of a problem all the time, since the objects our scientists and engineers think about are steadily shrinking (metamaterials are themselves an example). Each year scientists lose more direct access to their work; more of their landscape goes black. Tools for working around this problem have been invented, like the electron microscope and X-ray diffraction, but these are like canes for blind people: no substitute for direct observation. (To look at something with an electron microscope, for instance, you often have to coat the object being observed with metal and place it in a vacuum. Since this kills living things outright, it imposes serious limits on biological studies.) We have had no way to see living viruses infect cells, or to observe the interactions of proteins, or to watch DNA make a transcript of its biomolecular assembly instructions.

The same problem crops up everywhere. For instance, the advancement of the microcomputer industry depends on circuits with smaller and smaller features, but we must still use some form of light to print those features. Past a certain point—one we are very close to reaching—features become too little to be printed. The task becomes like using a crayon to write very fine letters. The farther we walk down this tunnel, the narrower it gets, and these days it is getting quite cramped indeed.

Pendry envisioned a way out of the tunnel, with metamaterials to guide the way. Tiny objects are difficult to observe because they have almost no reflection to focus on. But Pendry realized that when light hits a small object, the impacting radiation triggers a subtle effect that manifests itself as a pattern of local waves. The waves vanish without a trace almost immediately after being generated. Pendry thought that if metamaterials were built and positioned just right, they could pick up, preserve, and process these evanescent waves, converting them into a form that could be resolved into useful images. Normal lenses cannot produce images from such waves because of the limitations of how they bend light. But metamaterials can transcend those limits, providing a tight focus that no piece of glass (or any other ordinary material) ever could.

Pendry still remembers the day he realized that this new kind of lens would allow people to see invisibly small objects. "I was astonished and, frankly, frightened to publish the conclusion," he says, "because I knew that everyone's first reaction would be that it could not be true. I can tell you that I checked the result very many times!"

In 2004 researchers at the University of Toronto created the first superlens to tap into the minute details hidden in those evanescent waves, although the lens could focus only microwave radiation. The following year Zhang's team crafted an ultrathin layer of silver into the first optical superlens. Its resolution was several times better than that of the best optical microscopes. And in 2007 Zhang did even better by developing a lens that amplified the signal of the evanescent waves. The lens clearly resolved two nanowires separated by 150 nanometers, a gap narrower than a single wave of visible light. Pendry has no doubt that the "perfect lenses" he conceived will get steadily more powerful. “Fundamental physics sets no limits,” he says.

Pendry’s work on metamaterials is notoriously complicated and serious, so it is ironic that the most famous implication of his research—the invisibility cloak—began as a joke. Heeding the suggestion of a colleague, he decided to have some fun with a lecture he was delivering at a 2004 DARPA meeting. He knew metamaterials could theoretically hide objects from sight, so he made a Harry Potter reference—but not the one you might expect. He brought up Platform 9¾, the invisible departure point for Harry’s trip to Hogwarts, drawing some laughs from the crowd. “And then the DARPA woman started taking things seriously,” Pendry says. “She offered me half a million dollars to work on it.”

Soon afterward, Smith approached Pendry to tell him that he would like to build a cloak for real. “I told Smith he must be crazy, and then he did it,” Pendry says, chuckling.

In 2006, ensconced in his new lab at Duke University, Smith developed the first functional invisibility cloak, though not for visible light. The cloak steered radiation around a copper cylinder to hide the object from microwave detection.

From there, Zhang picked up the ball. By then he was set up at Berkeley, running a 40-person research group. While the projects Zhang oversees are varied, at the group’s core is a metamaterial fabrication shop, the most ambitious of its kind in the world. Foreshadowing the jolt that metamaterials is likely to give the general field of 3-D nanofabrication, the facility builds really small but geometrically complex devices.

That skill is necessary to get us to full-blown nanotechnology and to the long list of amazing devices (like universal fabricators, countertop food factories, intracellular longevity boosters, even telepathy implants) that it might make possible. However, almost all of engineers’ present expertise in building small objects involves two-dimensional structures, such as microprocessors and computer memory chips—in part because digital electronics generate lots of heat, and it is easier to cool something that is two-dimensional. Engineers have been speculating about 3-D chip architectures for years, but the change in skills and tools needed to build such devices is so radical that the feat has never found investment sufficient to do the job.

Until now.

With his metamaterials workshop, Zhang is the harbinger of change. Since so many metamaterials applications are inherently 3-D, the trickle-down from his work will be vast. For example, building a useful invisibility cloak—the kind that could hide a person or a military tank—requires crafting many little devices that pick up a ray of light on the far side of an object, away from the observer, and then relay that ray, row by row, around the object. When the ray arrives at the side facing the observer, it is re-emitted in the direction it would have taken had the object not been there at all. Very weird—and a decade ago it would have been considered a total violation of the laws of refraction—but seemingly doable. For the cloak to be useful, though, it would have to bend light from all directions. To do that, a 3-D array of light-bending devices is a must.

It was in the summer of 2008 that Zhang’s group took the first small step toward creating a real-world invisibility cloak by fabricating the first optical metamaterial to work in three dimensions. Made of 21 alternating sheets of silver and a glasslike substance, the material, dubbed fishnet, contains rectangular holes that resemble waffles or sieves. As light travels through the fishnet, the alternating layers act as circuits that bend light in unusual ways. A separate group in Zhang’s lab accomplished a similar feat using silver nanowires embedded in a solid base. In principle, a more durable version of these materials should be able to guide light around an object, creating the desired cloak.

This past January, Smith built a structure that comes even closer to the goal of building an invisibility cloak large enough to hide a person. The device is almost two feet long and four inches wide, with a small bump on one of the thin edges. If you place a small object beneath the bump and then shine microwave radiation on the cloak, the microwaves that bounce back will look like reflections from a blank mirror—as if the bump (and anything hidden beneath it) were not there.

The breakthrough in this work: Smith’s metamaterial device is the first to handle a very wide range of wavelengths, a necessity for Harry Potter–level invisibility. His design shows it is possible to cloak all the colors of an object at once, from red to blue and everything in between. The device is still a far cry from a wearable cloak—it works only on a flat surface, and it responds to microwaves, not light—but it is a big step in that direction. Smith says the design should easily scale down to the visible spectrum, meaning that soon we may see a “bump” of matter seemingly disappear in front of our eyes. Smith is betting that someone will build such a device by the end of this summer.

After that occurs, there will still be one big limitation: Anyone inside the invisibility cloak would not be able to see out, for the same reason that an outside observer could not see in. “If I can’t see you, you can’t see me. It would be like being inside a silvery bubble,” explains Pendry. Would-be invisible men will have to figure out a way to cut out a visor, or perhaps decloak before accidentally walking into a wall.

Yet other metamaterial applications focus not on vanquishing what we see but on extending it. Padilla hopes to use engineered materials to investigate what he calls “the last unexplored region of the electromagnetic spectrum”—the T-ray, or terahertz, region—positioned between the infrared and microwave bands, at a frequency of a trillion cycles a second. Still largely inaccessible to our instruments, T-rays, if captured, could lead to innovative imaging and sensing technologies that hold enormous potential in biomedicine and security.

Already NASA scans T-rays to look for weaknesses in the foam insulation on the Space Shuttle. T-rays offer hope for improved detection of cancer, including skin cancers like melanoma, because they track molecular signatures of malignancy that are not easily seen with other types of scans. Padilla also envisions terahertz radiation playing a huge role in airport security. Not only can T-rays penetrate clothing to expose objects hidden underneath, but, because of their size and frequency, they can also reveal “whether that object is cheese or a plastic explosive,” something current scanning technologies simply cannot do. In the world of astronomy, the specific frequency of T-rays would allow scientists to observe the formation of stars.

In search of these riches, Padilla is building a metamaterial-based terahertz camera. Currently some companies use expensive, inefficient high-powered lasers to scan objects with T-rays, but Padilla’s scanner should quickly and cheaply collect images in a device only slightly larger than your digital camera. The metamaterial, partially made from gold, will absorb T-rays and convert them to heat, which

Above: Xiang Zhang runs the cutting-edge metamaterials lab at the University of California at Berkeley. Right: The metamaterial known as fishnet, produced in Zhang's lab, could guide the design of an invisibility cloak in years to come.

SCIENTISTS ARE INHERENTLY DRAWN TO THINGS ONCE VIEWED AS FLAT-OUT IMPOSSIBLE.

FROM LEFT: PEG SKORPINSKI; JASON VALENTINE/UC BERKELEY

the camera can then detect to form an image. Padilla has begun experimenting with custom materials and expects to have a functioning terahertz camera within three years.

And yet, for all this optimistic talk, metamaterials researchers are finding that their science is still young and the technological hurdles vast. The electromagnetic spectrum consists of an immense number of wavelengths. The details of how each artificial material works, and the kinds of engineered elements it requires, vary with the particular wavelength being manipulated. Most research done with microwaves cannot be generalized to the infrared or the visible parts of the spectrum. Engineering solutions aimed at modulating each part of the electromagnetic spectrum must be reasoned out from the beginning and pursued with a different set of materials and designs. Further complicating things, many applications will work only if you process many sets of wavelengths simultaneously. (An invisibility cloak that screens out only yellow would not be very useful.)

Furthermore, light moving through materials typically gets absorbed until, at some point, the energy of the radiation falls to zero, putting an end to its usefulness. How can metaengineers move radiation through artificial materials without snuffing it out? Moreover, some frequencies of light have such short wavelengths that building devices to interact with them would require pushing fabrication expertise past its current limits. Pendry is working on finding new synthetic materials that maintain the quirky properties of metamaterials without absorbing the precious light. "It's bad enough in an ordinary lens, but it's terrible for a perfect lens," he says. Last October, Pendry published a paper in *Science* proposing new methods to allow engineers to harness light with minimal energy loss.

Like technical hurdles of the past, though, this one too will probably soon yield to science. The reward for success is just too great to fail: Contemporary technology rests on a huge family of structures that interact with electromagnetic fields, from wireless modems to permanent magnets to lasers to tuners of all kinds. All these devices stand to be significantly improved—made cheaper, smaller, more capable, faster. Metamaterials seem perfect for building tiny spectrometers tuned to the presence of specific molecules, a function of interest to everyone from the health care industry to the Office of Homeland Security. It should be possible to build radiation shields that allow objects to sit in fields without being affected by them. Then normal surgical tools, like scalpels, could be used in an MRI machine without distorting the images on screen. The principles of metamaterials could be extended to control water waves (protecting oil rigs from sudden storms, for instance) and sound waves (creating perfectly quiet, private spots in the middle of a noisy office).

Beyond all this, scientists are inherently drawn to things once viewed as flat-out impossible. "I would give a talk on metamaterials," remembers physicist Vladimir Shalaev of Purdue, "and people would come up to me and say, 'Vlad, you have such a good reputation. Why would you want to throw it away by working in this field? Don't you understand it cannot be true?' "

Now even his harshest critics have signed on for the show. Throw a rock into a pond and the ripples flow outward; toss a rock into a metamaterial pond and the ripples might flow inward, toward the point of impact. You could make the fish in that pond appear to swim in the sky. We aren't there yet, but Pendry and his growing band of followers are building the bridge.

Additional reporting by Andrew Grant