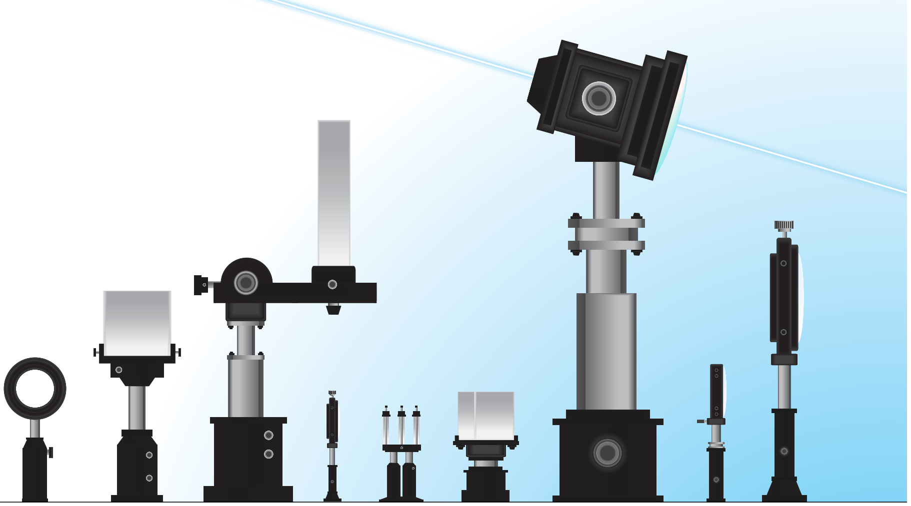
REFLECTIONS IN RESEARCH

At Caltech, mirrors are used to exploit the properties of light—allowing us to better understand life, matter, and the universe.

by Jessica Stoller-Conrad



You may not realize it, but when you took that one last look in your bathroom mirror this morning, you were casually using an essential research tool.

At their most basic level, mirrors are nothing more than smooth, polished glass with a metallic coating. Together, these simple components provide a reflection: the outgoing light that bounces off the mirror re-creates the initial image made by the incoming light.

Through its ability to reflect light, a mirror provides you with a uniquely accurate account of things that are difficult to see from your human perspective—whether it's a patch of unruly hair on the back of your head or the position of the car that's driving behind you on the freeway. Similarly, mirrors provide researchers at Caltech with a unique perspective into areas of science that might otherwise be unapproachable, giving them a way to peer into the microscopic world, examine the properties of unusual materials, and even search for that most elusive of all ripples in space-time, the gravitational wave.

GRABBING WITH LIGHT

Most introductory physics classes include a crash course in optics—the physics that explains the properties of light and its behavior when it comes into contact with different materials and instruments. As a young student reading through a physics textbook, however, Rob Phillips—now a Caltech biophysicist—had trouble seeing how this aspect of physics would ever connect with his intended research path.

"I studied physics kind of on my own, trying to avoid all parts of the subject that I thought were 'boring' at the time—and that included optics," Phillips says. "Since then, I've come to see that mirrors, lenses, and light are some of the most important tools in all fields of research—from physics to earth sciences, astronomy to biology. They're everywhere."

At Caltech, Phillips's research focuses on understanding how the laws of physics are reflected in the movement and makeup of biological structures, such as cells or DNA. Although theoretical modeling can predict the physical forces that move and control these microscopic building blocks of life, Phillips and his colleagues are able to actually study and quantify those forces by manipulating cells and other tiny structures using a tool known as an optical tweezer.

Rather than trapping objects between two metal pinchers as ordinary tweezers would do—a feat that would be impossible given the microscopic size of Phillips's samples—optical tweezers work by trapping tiny objects with beams of light. And while grabbing, trapping, and moving objects with beams of light might sound more like science fiction than science, optical tweezers are actually a standard tool in physical biology. But how *can* you control an object with light?

"That's not an easy concept to grasp, actually," quips Heun Jin Lee, a staff scientist in Phillips's lab and the group's resident expert on the use of these tweezers.

Lee uses a laser, mirrors, and lenses to harness the properties of light for the manipulation of tiny objects. A laser beam travels along a straight line of light, thanks to the light's steady, unchanging momentum. However, when the light passes through a transparent material, like a glass lens or water, the light waves propagate at a slower velocity than they did in the air. This change in velocity also causes a change in the light's momentum—which can result in the light's "bent" appearance, the beam changing direction upon reaching the surface of the material.

Since cells are mostly transparent they can act as this refracting—or light-bending—material in an optical tweezer. When the laser beam passes through the cell, the cell bends the light rays, and the light changes momentum—momentum that ultimately transfers from the light to the cell. For example, if you send two light rays from opposite directions at a cell on a microscope stage, the equal but opposite forces of momentum will in essence "trap" the cell in the intersection of the beams, Lee says.

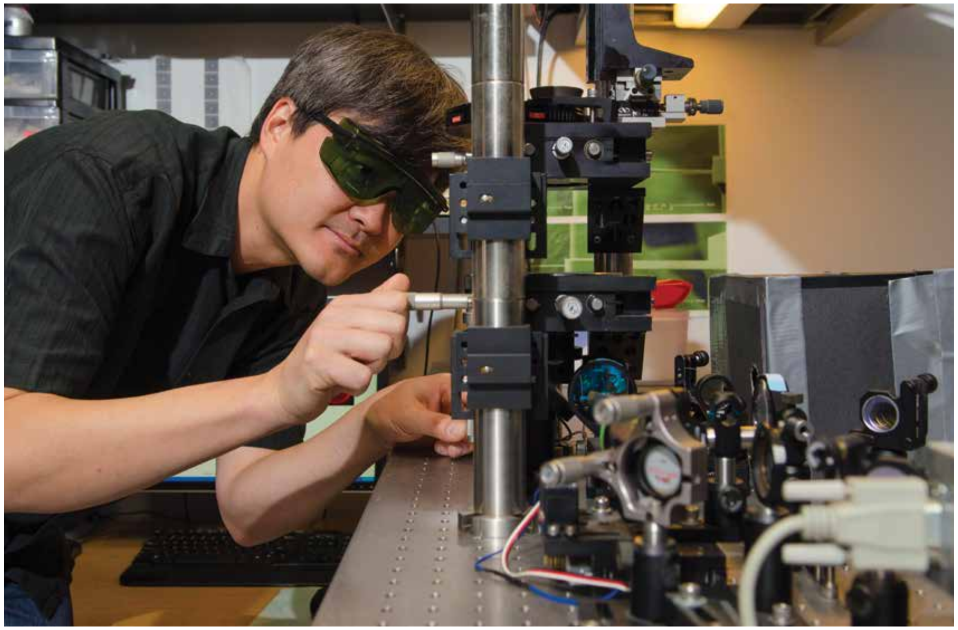
Creating an optical tweezer entails sending parallel rays of light from a laser beam through a series of lenses, each of which refracts—or bends—the rays at carefully calculated angles. Once the bent rays emerge from this optical obstacle course, they encounter a mirror that reflects—or redirects—the light beams onto a biological sample placed on the stage of a microscope. All of this is carefully calibrated so that, when the rays reach the stage, they intersect to form an X—trapping the particle of interest in the center of the X so that it can be held in place, moved around, or manipulated in whatever way the scientists desire.

"Normally when you're watching the microscopic world, stuff moves on its own; you're just an observer. With optical tweezers you're actually able to change things in the environment," says Phillips. "Using a joystick to direct the tweezers, you can capture a particle, hold it, and place it where you want it within three dimensions."

Optical tweezers have allowed Phillips, Lee, and their colleagues to perform a variety of experiments on very tiny objects. They've examined, for example, just how macrophages—cells that gobble up bacteria and cell debris in the bloodstream—prefer to ingest the long, skinny *E. coli* cells they encounter. Using optical tweezers, researchers are able to hand-feed *E. coli* cells to the macrophage in different orientations to observe the differences in the cell's eating habits. As it turns out, they prefer to eat *E. coli* that are approaching end-first; it's more difficult for the macrophage to ingest the bacteria sideways. Enabled by the physical properties of light and mirrors, the tweezers can help researchers gain such insights into how cells interact with objects in their environment.

The tweezers can also be used as a very sensitive device for measuring the force of a single moving cell. "We can capture a swimming *E. coli* and see it try to struggle out of the tweezers, and get a sense of the force that it uses—and match that with the amount of force you would predict," Lee says. If the *E. coli* was using no force at all, it would be perfectly centered in the beam; by measuring the distance between the bacterium and the center of the tweezers' beams, the researchers can determine the amount of force the cell is exerting as it swims. It's as if the *E. coli* were pulling on the basket of a tiny produce scale.

"It's remarkable that we can use these mirrors and microscope objectives—pretty old-fashioned optics—to focus laser light and manipulate microscopic particles," says Lee. "These components have been around for many years—and now we



Above: Staff scientist Heun Jin Lee adjusts the alignment of mirrors and lenses in an optical tweezer setup.

can use them to capture an *E. coli* cell or tie knots in a strand of DNA. A few decades ago it might have seemed crazy, but now it's just a standard tool."

UNFAITHFUL REFLECTIONS

Mirrors are predictable: when you look at yourself in the mirror, you can expect to see your own reflection, not someone else's. When light encounters a mirror, it faithfully bounces off, looking much the same as it did when it struck—a predictable behavior that falls under a branch of physics called linear optics.

However, materials can also exhibit nonlinear properties that allow an extremely small portion of the reflected light to look different from the incoming light. Physicist David Hsieh takes advantage of these small portions of reflected light to study the arrangement and symmetry of electrons in quantum materials.

Hsieh and his colleagues use a nonlinear optics technique called rotational anisotropy to see how the electrons are arranged within a material. The technique involves shining a laser through a labyrinth of curved and flat mirrors and eventually onto a small crystal made from the material of interest.

"In a typical mirror made of glass, the color of light being reflected is predominantly the color that goes in. But if one looks very carefully, there is a small amount of light reflected at a different color. For example, if you were to shine in red light, you might get some blue out," Hsieh says. "The relationship between the light that goes in and the nonlinear light that comes out tells you something about the way the electrons are arranged within the atoms of the crystal that linear optics would not."

Although the mirror maze isn't directly reporting information about electrons, the experiment would be nearly impossible without mirrors, Hsieh says. "One reason for these mirrors is because our lasers are just monsters," he says. "These instruments weigh hundreds of pounds, so it would be difficult to move them precisely enough to focus the light on a tiny crystal." Instead, the researchers create a path that bounces the light through the maze; by simply changing the angle of the mirrors, they can easily make adjustments to ensure that the laser lands squarely on the crystal.

Mirrors are also needed for another reason: the amount of light streaming from this "monster" laser—capable of providing light for hundreds of experiments at once—is way too powerful to run just a few individual experiments. Instead of using the laser at full strength, which might actually burn the crystal sample, Hsieh says that they use a second kind of mirror, "a sort of 'imperfect' mirror to get rid of some of that light. This mirror reflects some of the laser light, but most of it just goes through the glass. We can let most of the light go through, and take just what we need."

Once the laser beam has been tamped down with mirrors, the researchers can then use a series of lenses to focus the beam onto the crystal. They can then analyze the color of the light reflected off the crystal—and how it differs from the color of the light of the laser. This difference tells Hsieh and his colleagues a lot about how the electrons are collectively arranged around their atoms in the crystal—and how certain electron arrangements are associated with certain properties of the material.

They did this, for example, with crystals from the iridium oxide family of materials, which are known to have both strong electron-electron interactions (a property key to high temperature superconductivity) and equally strong electron-nucleus interactions (a property key to generating topological behavior where the material's surface and its interior act in two completely different ways).

When these two properties combine in the same material—iridium oxides—physicists don't really know what can happen, Hsieh says. The researchers hope that the information they've gathered about iridium oxide's electron symmetry can help device makers exploit the properties of iridium oxide in order to lower the power consumption of electronic devices or to create devices with brand-new functionalities.

"It's only been very recently—in the past few years—that people have recognized this class of materials, like iridium oxides, in which both electron-electron and electron-nucleus interactions are really strong," Hsieh notes. "The mirrors and lasers are essential to our experiments, and our experiments help us learn more about the arrangement of the electrons in these materials—and how these electron arrangements lead to useful properties. Electronics that are more energy efficient are one application of these materials, but no one knows what else this technology is going to bring."

CATCHING THE WAVE

Mirrors that direct a laser beam through a crystal help reveal what's behind the unique properties of various materials. What can mirrors show us when they instead direct two laser beams at one another?

A gravitational wave, says physicist Rana Adhikari. At least, he hopes that will be the case.

Gravitational waves—waves of gravitational force that are thought to create ripples in space-time—result from big cosmic events, like the spiraling merger of two stars or the collapse of large dying stars into a black hole. Although Albert Einstein's 1916 theory of general relativity predicts the waves, and researchers have seen evidence that supports their existence, they have yet to directly detect even a single gravitational wave.

Adhikari is hoping to change all of that by making improvements to the gravitational-wave detector at the Laser

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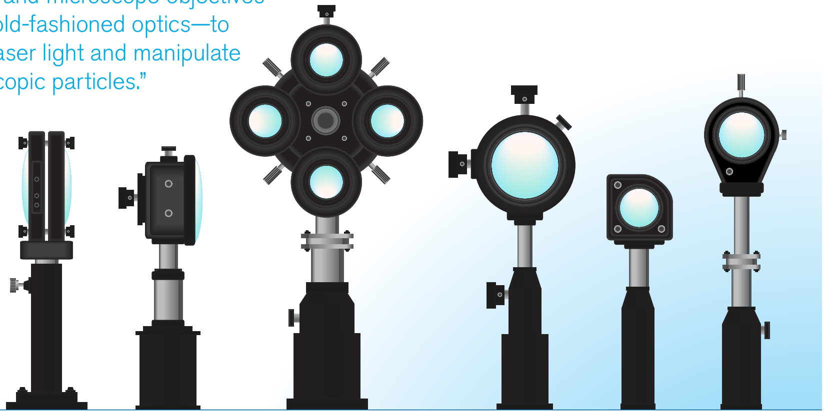


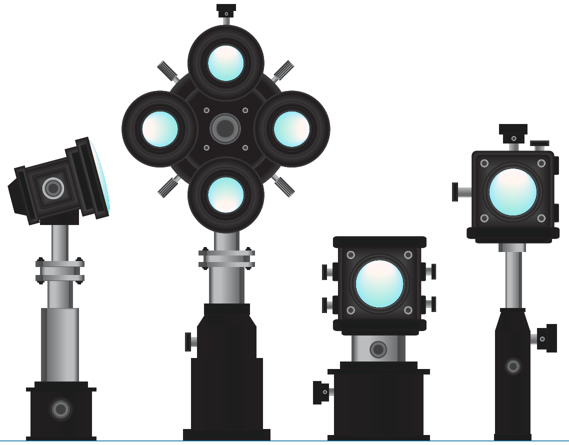
Interferometer Gravitational-Wave Observatory (LIGO)—improvements that depend on better and more precise mirrors. The LIGO facilities include gravitational-wave observatories operated by Caltech and MIT in Hanford, Washington, and Livingston, Louisiana, that began operations to detect gravitational waves in 2002. Experiments at both observatories ended in 2010 without any definitive sightings, but Adhikari and his colleagues—now armed with the best mirrors and lasers in the world—are working on an even more sensitive detector, called Advanced LIGO, that is slated to begin observations in 2015.

The laser interferometer that is the core of the LIGO observatories is the tool of choice for detecting gravitational waves. The detectors operate on the principle of interference in light waves. If two light waves with identical frequencies and amplitudes—such as waves split from the same laser—interact with one another, and the peaks and troughs of one wave are exactly aligned with those of the second wave, those two waves will combine into one big wave, with four times the energy of the initial wave. However, if the peak of one wave is aligned with the trough of the second wave, the two waves will cancel each other out, resulting in a net energy of zero.

It is this kind of alignment that's at the heart of the LIGO experiment, which involves identical, perfectly aligned waves of laser light that interact within the interferometer, which is an L-shaped tunnel with two 4-kilometer-long arms. A beam of laser light is split at the intersection of the arms, with each half sent down one of the paths. At the end of each arm is a mirror, which bounces the light back to that same intersecting point, near the beam's origin.

If the arms are exactly the same length—and nothing has affected the laser's path—the light from the two beams will interfere with one another, canceling each other out. "If you look at the output, there's nothing—it's totally dark," says Adhikari.

But, if something interferes with the path of the laser beam, the beams will no longer cancel out, and the changes to the resulting light will be detected. To prevent the mirrors from contributing to gravitational-wave false alarms, the arms of LIGO are actually long vacuum tubes, and the mirrors are insulated from vibrations via glass-fiber suspensions. Because geological activity, man-made activity, and even tumbleweeds blowing around outside the observatory could produce a false signal, LIGO also includes many other types of detectors that allow the scientists to subtract alternative possible causes of interference when they are detected. That way, when and if LIGO detects a gravitational wave, researchers will be sure it is indeed a gravitational wave—and not something else.



Interferometers have been used in research for more than a century—since first being developed by Nobel Prize-winning physicist Albert Abraham Michelson in the late 19th century. Although LIGO and Advanced LIGO use the same basic principles, science has made a lot of improvements since Michelson's time, Adhikari says.

"Michelson's device was only a couple of meters long, and the light would only bounce back and forth several times—the Advanced LIGO tubes are 4 kilometers long, so we effectively bounce the light about 200 times in each arm," he explains. Since each of the laser beams essentially travels 800 kilometers, there is more of an effect when a gravitational wave comes through and a greater likelihood that the detectors will sense a change in the beam's path. "That makes us extremely sensitive to even the smallest shifts—and thus, more sensitive to gravitational waves," says Adhikari.

Just how sensitive do these detectors need to be? "To catch a gravitational wave, we're trying to measure a back-and-forth motion that is approximately 10^{-19} meters in length," he says. "What does that even look like? The wavelength of light is 10^{-6} meters, and the thickness of my hair is something like 10^{-4} meters. These are the kind of distances we can imagine. But the motion we're wanting to detect is just so much smaller, it's almost *un*imaginable."

Right: Betsy Weaver, a detector engineer at Advanced LIGO in Washington, paints a polymer cleaning solution on the surface of the mirror; the polymer is used not only to clean the surface of the mirror, but also to protect the face of the optic from damage during handling.

Further improving on Michelson's interferometer concept, LIGO and Advanced LIGO are made even more sensitive to gravitational waves by the use of ultrasensitive components. For instance, the mirror coatings used were originally developed by the United States for defense purposes during the Cold War, and are some of the best in the world.

That need for the best and most advanced components applies to the mirrors as well. Because laser beams must bounce back and forth between the Advanced LIGO interferometer's large mirrors—which weigh in at 40 kilograms each—and because the more times this bouncing happens, the more likely the detector will be able to feel the tiny stretching of space-time that would represent a gravitational wave, the mirrors must be among the smoothest ever made.

"In our first-generation LIGO detector we had pretty good mirrors, polished with the standard abrasives, but we wanted the best for Advanced LIGO, so we went with this company that is famous for doing telescope optics, called Tinsley," says Adhikari. "They measure the flatness of the mirror with an extremely good interferometer, and if it's a little bit curvy, they shoot it with this particle beam and they knock single atoms off the surface until the mirror gets flatter. It takes a long time, and they are expensive optics, but they will be the best in the world."

Now *there's* a mirror that might have caught the attention of a young Rob Phillips as he was leafing through a dry physics textbook.

"I may have thought it was boring to learn about at the time, but I was completely wrong," Phillips admits. "Optics is one of the main reasons I switched from physics to biology and, in my view now, it's one of the coolest things in science." E&S

Rana Adhikari is a professor of physics. His work on LIGO is funded by the National Science Foundation.

David Hsieh is an assistant professor of physics. His work is funded by the Department of Energy, the Department of Defense, the Army Research Office, and the Caltech Institute for Quantum Information and Matter.

Heun Jin Lee is a staff scientist.

Rob Phillips is the Fred and Nancy Morris Professor of Biophysics and Biology. His work is funded by the National Institutes of Health.