NEWS

Doing the Wave in Many Ways

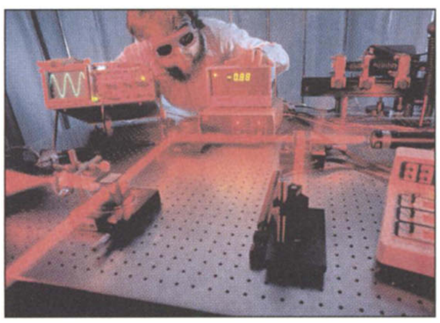
"Kaleidoscopic" doesn't begin to describe the variety of niches coherent waves have come to fill since scientists started giving them their marching orders. This sampler presents a few of the more prominent applications researchers have found for coherent light, sound, particles, and atoms

Laser Light

The jewel in the coherence crown is undoubtedly the laser, which has infiltrated every cranny of modern life. Light waves don't naturally march in step—a beam from a flashlight is not coherent—but a laser beam is coherent because it exploits a peculiarity of atoms.

If you pump the right amount of energy into an atom, you can excite it, causing an electron to flit about at a much higher energy than it ordinarily would. Left to itself, the excited atom would eventually spit out a photon carrying the extra energy and relax back into its ground state. Instead of waiting, though, you can tickle the atom with another photon with that characteristic energy. This induces the atom to disgorge a photon, which then moves in lockstep with the photon you used to tickle the atom. The two photons encounter other excited atoms, which spit out more photons that move in lockstep, which encounter more atoms, and soon you have a powerful, coherent beam of light.

What can you do with that light? Interfere it with itself, measure distances, focus an enormous amount of power on a small spot many meters away, use it to carry messages without having it scatter away, and many other applications. That is why scientists are constantly trying to broaden the types of lasers available: making them out of silicon, getting them to emit shorter and shorter wavelengths, and coaxing them to fire over a shorter and shorter time span.

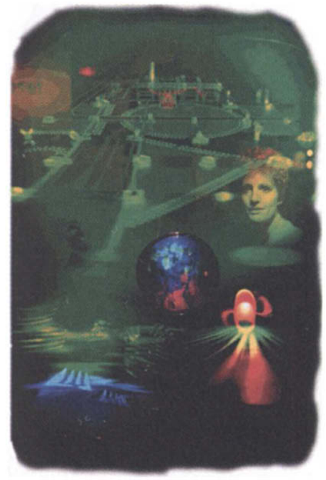


Lasers can scan a price tag, burn out a tumor, or measure the distance to the moon.

Holography

Ordinary photographs are flat, purely two-dimensional images. The illusion of depth is superficial; if you move your head to the side, your perspective on the scene doesn't change. Holography, by contrast, uses coherent light to give a real 3D view of an object. If you move to the side while gazing at the holographic portrait of a person, a face-on view will become a profile.

Holography exploits coherence and interference patterns to achieve what an ordinary photograph can't. In one scheme, the holographic "camera" is a fancy interferometer. One beam illuminates the target and is reflected onto a photographic plate, but before striking the plate, it is combined with a "reference" beam that interferes with the light coming from the target. The plate records an interference pattern. A laser light, shined on the plate, reconstructs from that interference pattern the original image in three dimensions. Unlike a photograph, which can't be reconstructed when cropped, a small segment of the hologram contains information about how to reconstruct the entire image (albeit at lower resolution).



More than just 3D slide shows, holograms can probe atoms and store huge amounts of data.

Holography isn't merely about pretty pictures. Some scientists are using short-wavelength beams, such as x-rays or neutrons, to make holograms of objects as tiny as atoms, giving fully 3D views of subatomic structure. Others are using the enormous amount of information in a hologram to store data—with greater densities and faster access times than can be achieved with a magnet-based hard disk.

Interferometers

Because coherent beams march in step, they are perfect for interferometry: the measurement of interference between two or more beams.

Waves behave like a series of crests and troughs. When waves from two sources combine, what happens depends on the waves' phases—the timing of when their crests and troughs strike a given point. If the waves are in phase, then when they are combined, their crests arrive at the same place at the same time. The crests reinforce each other, making bigger crests; likewise for the troughs. The two beams, combined, are brighter than each individual beam. If they are exactly out of phase, though, a crest meets a trough, a trough meets a crest, and the waves cancel each other. The combined beam is dark.

An interferometer takes advantage of this property by splitting a beam into two identical beams, sending them down two different paths, and then recombining them. If the paths are the same length, the beams will still be in phase when they recombine; the detector sees a bright beam. If one path changes length a fraction of the wavelength of the beam, then the detector sees the beam dim and then disappear. Because visible light wavelengths are a few hundred nanometers, the interferometer is sensitive to changes in distance much smaller than a human could measure by hand.

Laser Interferometer Gravitational Wave Observatory in Hanford, Washington.

A CD player uses a laser interferometer to measure tiny pits on the disk, which a digital player interprets as bits. And the Laser Interferometer Gravitational Wave Observatory, operating simultaneously in Washington state and Louisiana, uses two enormous interferometers in hopes of picking up a gravitational wave, which would change the distance between two mirrors by much less than the diameter of an atom.

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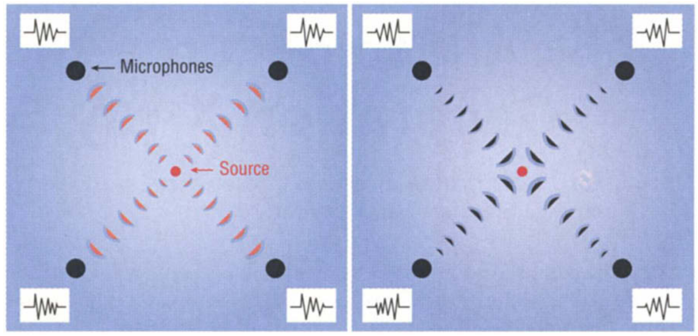
Acoustic Waves

Sound is a wave, although it's not precisely like a light wave or a water wave. Those are transverse waves, in which the wave motion is up and down or left and right. Sound waves are compression waves, alternate rarefactions and compressions of a material such as air. And a single-frequency sound source such as a tuning fork emits waves that are all in phase: They are coherent, at least until the medium they travel through destroys the coherence.

A little less than a decade ago, physicists such as Mathias Fink of the University of Paris VII realized that they could exploit that property to focus an enormous amount of sound energy on a given point in space. All they had to do was "reverse time."

Set up an array of detectors in the right place in, say, the ocean, and they can easily pick up the sound of a point source such as a submarine pinging its sonar. Because the ocean is a messy place, littered with silt and temperature gradients and bubbles and such, the waves will get distorted en route to the detectors. Even if the sensors are parked on a sphere around the source, each will detect a slightly different sound wave. But Fink and others realized that if each detector then took what it heard, reversed it, amplified it, and played it back into the ocean, all these different-sounding waves would travel back where they came from and would all converge at the same time, with the same phase, on the original source. The sonar ping would hit the sub with tremendous strength.



By recording sound, amplifying its energy, and sending it back to its source, "time-reversal mirrors" could use the noise of an enemy submarine against it.

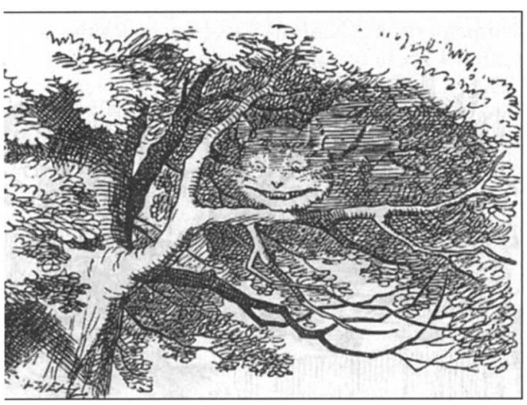
Sub hunters hope to use these "time-reversal mirrors" to pinpoint enemy subs with great precision, and doctors hope to focus ultrasound energy to break up kidney stones without damaging surrounding tissue.

Quantum Effects

Schrödinger's cat: alive or dead? It's a matter of coherence, or more precisely, decoherence. Quantum objects such as atoms and photons behave differently from macroscopic ones such as cats or rocks. Thanks to a property known as superposition, for example, a small thing like an atom can be both spin up and spin down at the same time, but a large thing like a cat (to cite physicist Erwin Schrödinger's classic example) can't be simultaneously alive and dead.

What makes quantum objects quantum and macroscopic objects macroscopic? It seems to have to do with the process by which quantum objects lose their quantum nature: decoherence. (In a sense, a coherent beam of light behaves like a single quantum object.) When a photon or an atom is measured, it is forced to "choose" whether it's spin up or spin down, and at that moment, it behaves like a classical object rather than a quantum one. The quantum state decoheres.

Decoherence can strike when information flows from the object into the outside world—from a measurement or from the stray bounce of a molecule of air. The bigger and warmer an object is, the more difficult it is to isolate it and prevent information from flowing from it into its environment, making it decohere more and more quickly. This hemorrhage might be what makes big things behave very differently from small things: Macroscopic objects might have a quantum nature, but it disappears too quickly to measure, leaving behind only the grin of Schrödinger's cat.

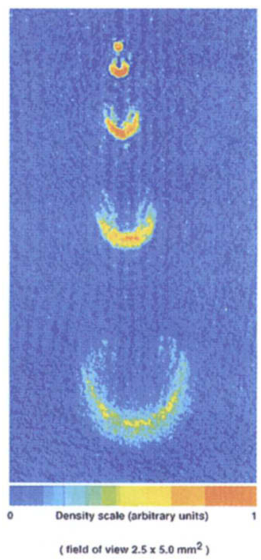


Decoherence may explain why the quantum properties of familiar objects vanish unnoticed.

Matter Waves

Light behaves like both a particle and a wave. So does matter. Individual electrons, for example, can interfere with themselves, leaving "dark" and "light" spots on a detector just as photons do. And just as a traditional laser creates coherent beams of light waves, an atom laser would create coherent beams of matter waves.

Cool certain types of atoms enough to still almost all of their jittery thermal motion, and their waves will overlap. The atoms lose their individuality and begin to act like a single superatom: a giant, coherent lump of matter known as a Bose-Einstein condensate (BEC). In 1997, Wolfgang Ketterle, a physicist at the Massachusetts Institute of Technology, allowed matter from a BEC to leak out of its cage, dripping down under the influence of gravity. Although hardly a robust beam like a traditional laser, it was an atom laser of sorts: Matter waves, all locked in phase, were marching in the same direction. Since then, researchers have been improving the brightness and robustness of these beams. Even though atom lasers are nowhere near as bright as an ordinary laser, they have a potentially important advantage: The wavelength of a chunk of matter is much, much smaller than that of a beam of anything but the highest energy light. Because of this small wavelength, an atom laser could do finer work than an ordinary laser can. A matter interferometer could sense much smaller distance changes, a matter hologram could image much tinier features, and an atom laser could, in theory, create structures in silicon or other materials that are far too small for lasers to make. —CHARLES SEIFE



Faint matter waves from an "atom laser" could prove handy for fine etching and imaging.

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