Finding your way out of the woods with GPS? Hanging a picture frame with a laser level? Making photocopies? Better thank Einstein

By Philip Yam

EVERYDAY EINSTEIN

To provincial Manhattanites, Queens County is known only as the place where New York City keeps its airports and where the Mets play baseball. One Saturday afternoon, when I didn't have a flight to catch and the Mets were out of town, I ventured to the northeast part of Queens—specifically, to the College Point neighborhood. There, in a strip mall stretching along a congested 20th Avenue, I went to look for Albert Einstein.

Not surprisingly, Einstein's ideas are essential in many kinds of scientific research, enabling physicists to accelerate particles to near light speed and permitting astronomers to measure and model celestial phenomena. But Einstein's contributions over his life also extend deeply into our everyday encounters with technology. His descriptions of how light can act as particles, how atoms can emit radiation, and how velocity and gravity affect clocks are all important to making common devices work today.

At the College Point mall, my first interaction with Einstein happened as I entered the giant discount store Target. The doors swung open after a photocell—an "electric eye"—spied my approach. The sensor, made from a semiconductor sandwiched between two electrodes, responds to light. As the intensity of light varies—by the breaking of a light beam, say, or a decrease in general illumination—the amount of current generated by the sensor changes. Coupled to appropriate circuitry, it can trigger the doors to open.

Such sensors represent an application of the photoelectric effect, in which light falling on metal sends electrons flying off it. Einstein did not discover the phenomenon, which was first noticed in France in 1839. He did, however, correctly explain it while puzzling out the calculations of German physicist Max Planck. Based on observations, Planck in 1900 figured that a heated body releases light of a given frequency, or color, in discrete amounts called quanta. Planck derived his now famous constant, h, to make the equations describing this so-called blackbody radiation work out.

OVERVIEW

- Einstein's theories enable several kinds of consumer technology to work.
- The photoelectric effect forms the basis of solar cells and electronic light detectors.
- The stimulated emission of radiation is the foundation of lasers.
- Relativity provides the needed corrections for GPS.

ANTHONY MARINO

EINSTEIN FOR SALE: The physicist's influence extends to solar-powered devices, GPS units, digital cameras, and lasers in DVD players, levels and cat toys.

But Einstein theorized that *h* was more than a mathematical patch. He postulated that light, rather than flowing as a continuous wave of energy, travels in packets. With his 1905 analysis, along with subsequent papers, Einstein showed that light can behave as a stream of particles; when it does, it knocks electrons out of the metal in the way a cue ball breaks a billiard rack.

Einstein also explained a baffling feature of the photoelectric effect. Although the intensity of light sent more electrons shooting off the metal, the velocity of the liberated electrons remained the same no matter how dim or bright the light was. The only way to change the velocity of the electrons was to use a different color of light. To account for the observation, Einstein figured that the energy of each light particle, or photon, depends on its frequency multiplied by *h*. Subsequent experiments confirmed Einstein's predictions, and for his explanation of the photoelectric effect, Einstein won the 1921 Nobel Prize in Physics.

The photoelectric effect today underlies instruments that turn on the streetlights at dusk, regulate the density of toner in photocopy machines and govern the exposure times of cameras—in fact, it is involved in just about any electronic device that controls or responds to lighting. Photoelectric devices are even used in Breathalyzers—the photocell picks up a color change appearing after a test gas has reacted with alcohol. The effect also led to the invention of photomultipliers, which consist of evacuated glass tubes containing a series of metal steps. The steps cough up successively more electrons after an initial metal target is struck by photons. In this way, a weak light signal is amplified. Photomultipliers channel light in astronomical detectors and television cameras.

The most visible application of the photoelectric effect is in solar, or photovoltaic, cells. Pioneered in the 1950s, solar cells convert 15 to 30 percent of the incident light into electricity and power calculators, watches, environmentally conscious homes, orbiting satellites and Martian rovers.

Stimulated Thinking

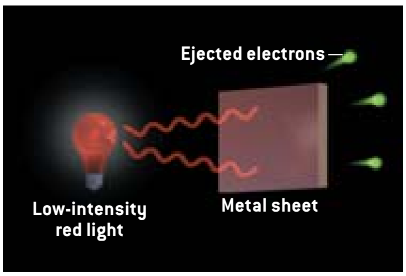
BACK AT THE MALL, I see that against the walls lining Target's electronics section, just beyond the 30 checkout registers, are stacks of DVD and portable CD players, some costing as little as $12.99. The registers and players all use some kind of photocell, but what is more interesting from an Einsteinian perspective is the red beam of coherent light they shoot. The now ubiquitous laser owes its existence to a theoretical framework erected by Einstein in 1917.

With his paper "On the Quantum Theory of Radiation," Einstein continued to explore light and matter. In par-

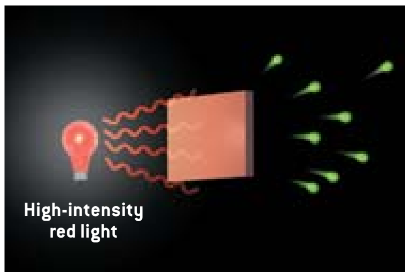
THE PHOTOELECTRIC EFFECT

Making Waves and Particles

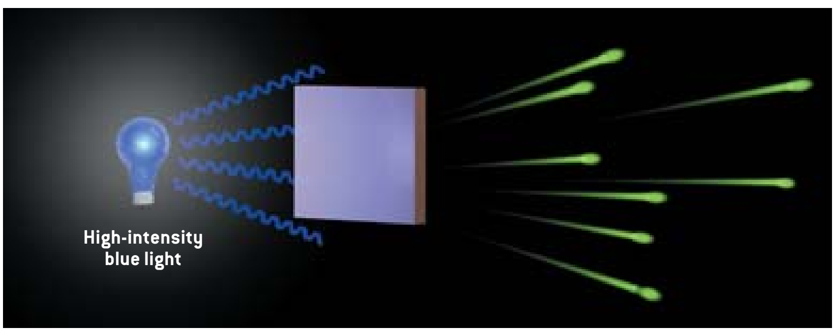
The photoelectric effect, exploited in sensors, solar cells and other electronic light detectors, refers to the ability of light to dislodge electrons from a metal surface. One aspect of the effect is that the speed of ejected electrons depends on the color of the light, not its intensity. Classical physics, which describes light as a wave, cannot explain this feature. By deducing that light could also act as a discrete bundle of energy—that is, a particle—Einstein accounted for the observation.



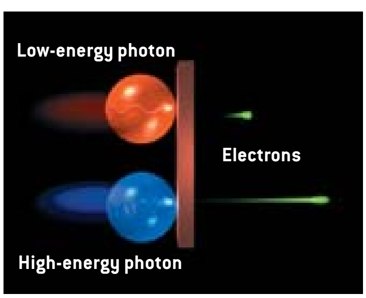
1 Red light sends electrons flying off a piece of metal. In the classical view, light is a continuous wave whose energy is spread out over the wave.



2 Increasing the brightness ejects more electrons. Classical physics also suggests that ejected electrons should move faster with more waves to ride—but they don't.



3 Changing the light to blue results in much speedier electrons. The reason is that light can behave not just as continuous waves but also as discrete bundles of energy called photons. A blue photon packs more energy than a red photon and essentially acts as a billiard ball with greater momentum, thereby hitting an electron harder (*right*). The particle view of light also explains why greater intensity increases the number of ejected electrons—with more photons impinging the metal, more electrons are likely to be struck.



ALFRED T. KAMAJIAN

The idea of correcting for relativity was not obvious to the original GPS designers.

ticular, he realized that atoms can become excited—that is, jump to a higher energy level—if they absorb light. They spontaneously emit light to return to a lower level.

In addition to absorption and spontaneous emission, Einstein deduced that a third kind of interaction must exist, one in which a photon could induce an excited atom to emit another photon. These two photons in turn could stimulate two other atoms to emit photons, yielding four photons. Those four photons could lead to eight more, and so on.

The trick to creating a coherent beam would be establishing a "population inversion"—having more atoms excited than not excited—and finding a way to allow the photons emitted to accumulate into an intense beam. That wouldn't happen until 1954, when Charles H. Townes of Columbia University and his colleagues devised the laser's predecessor, the "maser" (*m*icrowave *a*mplification through *s*timulated *e*mission of *r*adiation).

In retrospect, "it is a wonder that invention of the laser took so long," Townes wrote in his 1999 memoir, *How the Laser Happened.* "[The] laser could have happened 30 years earlier than it did." One possible reason: although Einstein's equations state that stimulated emission produces additional photons, they do not explicitly indicate that it produces exact copies, identical not just in frequency but also in phase. Light sources such as the sun and tungsten filaments produce plenty of photons of the same frequency, but they are out of step—they produce the optical version of random noise. Get all the photons to be coherent—to play the same note at the same time—and the result will be a singular roar rather than a dull hiss.

Einstein "never considered coherence," surmised Townes, now at the University of California at Berkeley. But "I feel sure that if asked, Einstein would have quickly concluded there must be coherence and that if one had enough atoms in an appropriate upper state, one would get net amplification."

Even if some physicists recognized that the photons would be coherent, Einstein's calculations showed that stimulated emission would rarely occur. "It's an incredibly small effect that Einstein predicted, so I don't think people appreciated the significance," says Carlos R. Stroud, a quantum optics physicist at the University of Rochester. Or, as Stroud's colleague Emil Wolf puts it: "Einstein was years and years ahead of everyone else."

In the decades after the 1917 paper, sporadic references to creating stimulated emission appeared, but none of the ideas were pursued. The key ingredient to making amplified radiation, Townes realized in the early 1950s, was a resonant cavity. In lasers—invented a few years after the maser—the cavity is simply the space contained by two mirrors, so that the light bounces back and forth, building up in intensity until a beam emerges from one of the mirrors (which is partially transmitting).

Armed with the basics, engineers found they could make lasers from many substances—including Jell-O infused with fluorescent dye and even tonic water. Widespread use of lasers came about thanks to the semiconductor industry and to the design of light-emitting diodes. Indeed, stimulated emission occurs in an astonishing array of products. Besides DVD players, levels and pointers, lasers are behind ring gyroscopes in aircraft, commercial cutting tools, medical instruments and communications signals through fiber optics. Lasers have become indispensable in science, earning Nobel prizes for several investigators who used them to study chemical reactions and to manipulate microscopic objects, to name two. Masers act as accurate clocks for the U.S. Naval Observatory and amplify faint radio signals in astronomy studies.

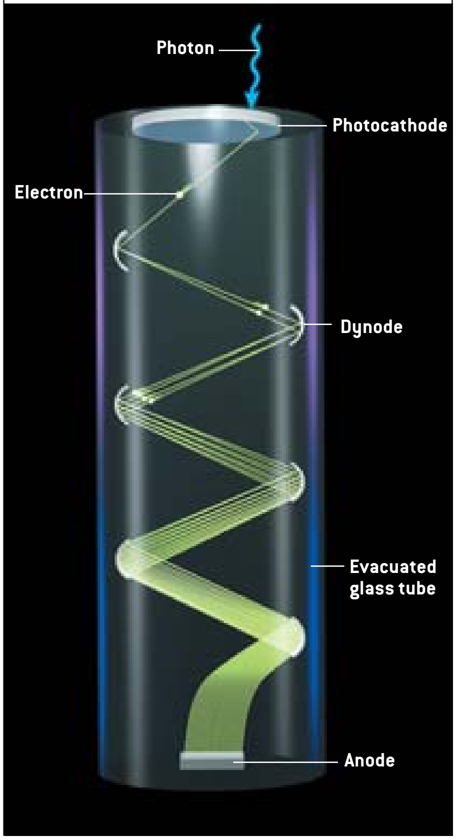
GPS Ticks

MY NEXT STOP inside Target was the outdoor sports section, but unable to find my quarry, I backtracked to the electronics department. "Do you have GPS devices?" I asked at the

PHOTOMULTIPLIERS

Light Work

The photomultiplier tube, essential in video cameras, exploits the photoelectric effect to convert illumination into electrical impulses. A photon hits a metal called a photocathode, which ejects an electron. Magnetic fields from surrounding coils (*not shown*) guide the electron to another kind of metal, called a dynode, which when struck by an electron emits additional electrons. Successively positioned dynodes thereby boost the number of electrons, which reach the anode and produce a signal.



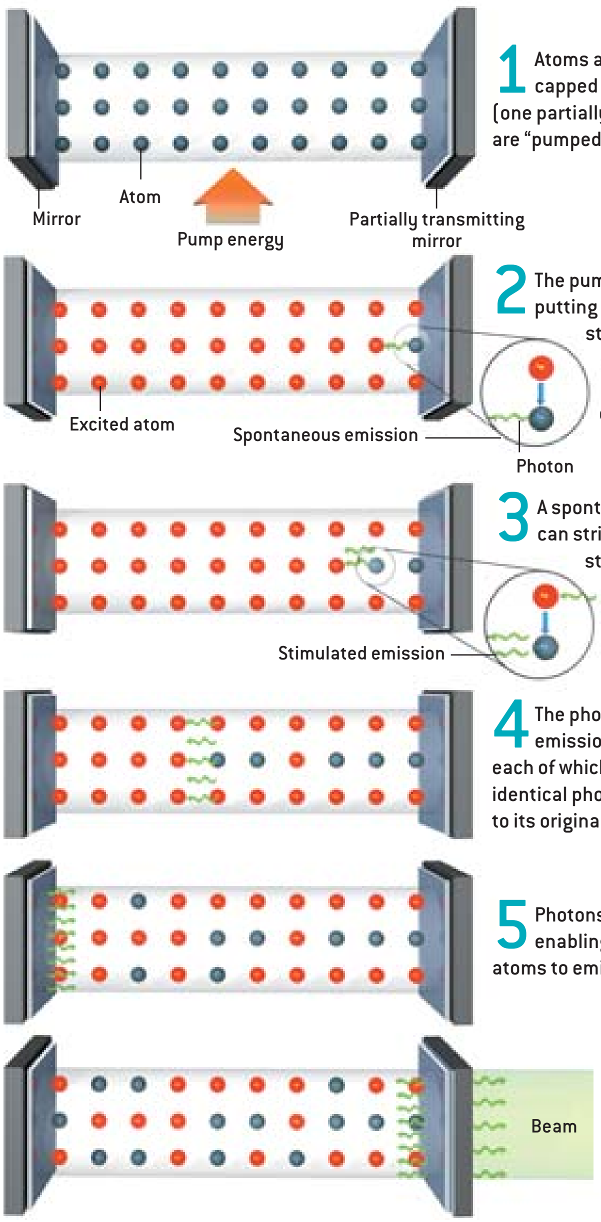
ALFRED T. KAMAJIAN

Lasers can be made from many substances—including **Jell-O infused with fluorescent dye** and even tonic water.

STIMULATED EMISSION

The Brightest Lights

The laser (and its microwave cousin, the maser) results from the stimulated emission of photons (radiation) by excited atoms. Einstein predicted the existence of the process in 1917, and today lasers form the basis of many consumer products, including pointers, levels and DVD players.



1 Atoms are contained in a cavity, capped at the ends by two mirrors (one partially transmits light). The atoms are "pumped" with an infusion of energy.

2 The pump energy excites the atoms, putting them in a higher-energy state. Some atoms will spontaneously emit a photon and drop back to their original, unexcited state.

3 A spontaneously emitted photon can strike an excited atom, stimulating that atom to emit an identical photon.

4 The photons can further stimulate emission from other excited atoms, each of which contributes an identical photon when reverting back to its original state.

5 Photons reflect off the mirror, enabling them to stimulate other atoms to emit photons.

6 Some photons will leak past the partially transmitting mirror, forming a coherent beam out of the cavity.

ALFRED T. KAMAJIAN

counter. "Not no more," came the reply.

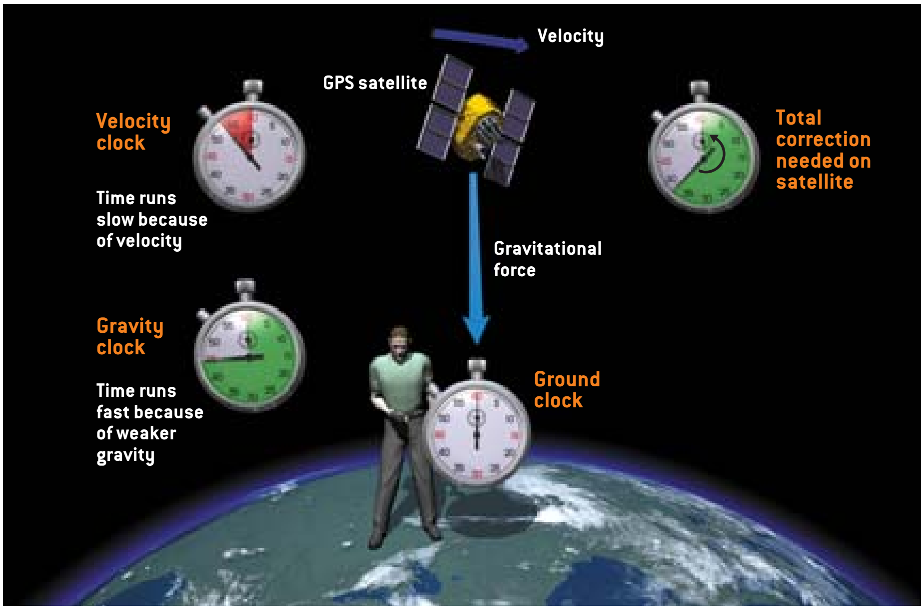
The Circuit City next door, however, offered several models, a few less than $200. These handheld instruments provide latitude, longitude and altitude by picking up timing signals from Global Positioning System satellites. Accurate distance measurements require accurate timepieces, which is why each of the 24 GPS satellites carries an atomic clock [see "Retooling the Global Positioning System," by Per Enge; SCIENTIFIC AMERICAN, May].

Today most store-bought GPS receivers can pin down your position to within about 15 meters. Accuracy of less than 30 meters, notes physicist Neil Ashby of the University of Colorado at Boulder, assuredly means that a GPS receiver incorporates relativity. "If you didn't take relativity into account, then the clocks up there would not be in sync with the clocks down here," elaborates Clifford M. Will, a physicist at Washington University. Relativity states that fast-moving objects age more slowly than stationary ones. Each GPS satellite zips along at about 14,000 kilometers per hour, meaning that its onboard atomic clock lags the pace of clocks on the earth by about seven microseconds per day, Will calculates.

Gravity, however, exerts a greater relativistic effect on timing. At an average of 20,000 kilometers up, the GPS satellites experience one fourth of the gravitational pull they would on the ground. As a result, onboard clocks run faster by 45 microseconds per day. An overall offset of 38 microseconds thus has to be figured into GPS. "If you didn't have frequency offset in satellites, then an 11-kilometer-per-day error would build up," Ashby explains. (The effects are actually more complicated because the satellites follow an eccentric orbit, traveling closer to the earth in some

Time and Time Again

Global Positioning System requires relativistic corrections. Because of the velocity of GPS satellites, onboard clocks run about seven microseconds slower per day than ground clocks. The weaker gravitational pull on the satellites adds another relativistic effect, making clocks run 45 microseconds faster per day. Hence, a correction factor must be calculated that effectively turns back onboard clocks by 38 microseconds per day to yield accurate GPS data. Relativistic errors cancel out in GPS receivers enabled with the wide-area augmentation system (WAAS), because the units rely on additional signals from ground locations.



instances and farther away at others.)

The idea of correcting for relativity was not obvious to the original GPS designers, mostly military engineers, back in the 1970s. "It was controversial," recalls Ashby, who served as a consultant. "Some people believed you had to account for it; some didn't." So divided were the designers that the first GPS satellite was launched without the frequency offset but had a switch to turn on the offset just in case. It quickly became apparent that the switch had to be on, Ashby says.

Newer GPS methods are less dependent on correcting for relativistic effects, at least for positional data. In differential GPS, which requires receivers at known ground locations in addition to the handheld unit, the offset errors effectively cancel out. (The approach is called the wide-area augmentation system, or WAAS.) But those who use GPS to keep track of time, such as radio astronomers, still need Einstein by their side.

Einstein as Inventor

EINSTEIN DID HAVE one type of invention that, alas, can't be found at the mall I visited—or at any mall, for that matter. His dabbling in appliance making may not have produced any durable consumer goods, but the related mechanisms that he patented are in use elsewhere. With fellow physicist Leo Szilard, Einstein came up with refrigerator designs in the 1920s. The machines relied on electromagnetic pumps that did not leak (cooling gases back then were toxic). The invention of safer refrigerants quickly rendered the leakless pump obsolete, and Einstein's fridge never appeared in appliance showrooms. The pump, however, survives as a means to move sodium to cool a type of nuclear reactor called a fast breeder [see "The Einstein-Szilard Refrigerators," by Gene Dannen; Scientific American, January 1997].

Of course, the inventor's yen did not propel Einstein, who was primarily driven by the desire to understand nature. He left the technological consequences of his reasoning to others. The same could be said of $E = mc^2$, a relation that emerged from his 1905 relativity paper. "Before that, people had not considered that matter was in any way convertible to energy," Stroud remarks. Given its seductive simplicity—multiply a tiny bit of mass with the speed of light squared to get a lot of energy—there had to be ways to see it in action. "I suspect it got a lot of people thinking about it," Will surmises.

Certainly, in making the fission bomb, the Manhattan Project scientists were motivated by imperatives more pressing than confirming that E really does equal mc^2. It is one of Einstein's technological legacies that still might radically change the world—and assuredly one never to be sold at a shopping mall. SA

Philip Yam is news editor.

MORE TO EXPLORE

How the Laser Happened: Adventures of a Scientist. Charles H. Townes. Oxford University Press, 1999.

Relativity and the Global Positioning System. Neil Ashby in *Physics Today,* Vol. 55, No. 5, pages 41–47; May 2002.

Einstein on the Photoelectric Effect. David Cassidy. **www.aip.org/history/einstein/essay-photoelectric.htm**

ALFRED T. KAMAJIAN