EVERYONE KNOWS OF THE SPEED OF LIGHT AS one of the unshakable properties of the universe. It’s not surprising, then, that experiments to radically alter light’s speed require some serious equipment and hard work. Running such an experiment requires first a careful tune-up and optimization of the setup and then a long period of painstaking data gathering to get a consistent set of measurements. At the Rowland Institute for Science in Cambridge, Mass., our original slow-light experiments typically took place in stints lasting 27 hours nonstop. Instead of breaking for meals, we learned to balance a slice of pizza in one hand, leaving the other clean to flip mirrors in and out on the optics table during 38 seconds of total darkness at a crucial stage of each run.

Our goal was to drastically slow down light, which travels through empty space at the universe’s ultimate speed limit of nearly 300,000 kilometers a second. We saw the first sign of light pulses slowing down in March 1998. As happens so often in experimental physics—because it can take so many hours to get all the components working together for the first time—this occurred in the wee hours of the morning, at 4 A.M. By July we were down to airplane speed. At that time I had to go to the Niels Bohr Institute in Copenhagen to teach a class. I remember sitting in the plane marveling that I was traveling “faster than light”—that I could beat one of our slow pulses to Denmark by a full hour.

Needless to say, I was restless during the week in Copenhagen and eager to get back to Cambridge to continue the light-slowing experiments. In the next month we reached 60 kilometers per hour and decided that it was time to publish. The real payoff for the hard work, prior to those results, was sitting in the lab in the middle of the night and observing the slow-light pulses, knowing that we were the first in the world to see
FREEZING OF LIGHT begins with a process in which a carefully tuned laser beam renders an opaque material transparent to a second laser beam.
light go so slowly that you could outpace it on a bicycle.

Late last year we took this process to its logical but amazing conclusion: we brought pulses of light to a complete halt within tiny gas clouds cooled to near absolute zero. We could briefly keep the pulses on ice, so to speak, and then send them back on their way.

As well as being of great intrinsic interest, slowing and freezing light have a number of applications. At sufficiently low temperatures the ultracold clouds of atoms used in our slow-light experiments form Bose-Einstein condensates, remarkable systems in which all the atoms gather in a single quantum state and act in synchrony. New studies of Bose-Einstein condensates will be made possible by, for example, sending a light pulse through a condensate as slowly as a sound wave, which we expect will cause a wave of atoms to “surf” on the light pulse.

The slow and frozen light work also opens up new possibilities for optical communications and data storage and for quantum-information processing—that is, for quantum computers, which would utilize quantum phenomena to outperform conventional computers. The freezing-light system essentially converts between motionless forms of quantum information and photons flying around at the usual speed of light.

Getting Atoms into a State

Many Ordinary Materials slow down light. Water, for instance, slows light to about 75 percent of its velocity in a vacuum. But that type of speed reduction, associated with a material’s refractive index, is limited. Diamond, which has one of the highest refractive indices of a transparent material, slows light by a factor of only 2.4. Reducing light’s speed by factors of tens of millions requires new effects that depend on quantum mechanics. My group produces the conditions for these effects in a cigar-shaped cloud of sodium atoms—typically 0.2 millimeter long and 0.05 millimeter in diameter—trapped in a magnetic field and cooled to within a milliionth of a degree of absolute zero.

Sodium belongs to the family of alkali atoms, which have a single outermost, or valence, electron. The valence electron produces almost all the action: Different excited states of a sodium atom correspond to that electron’s being promoted to larger orbits around the nucleus, with higher energies than its usual lowest energy state, or ground state. These states determine how the atom interacts with light—which frequencies it will absorb strongly and so on. In addition, both the valence electron and the atom’s nucleus are magnets, in effect acting like tiny compass needles. The electron’s magnetism is associated with its intrinsic angular momentum, or spin, a little like the association of the earth’s rotational axis with magnetic north but with exact alignment. The precise energies of an atom’s excited states depend on how the spins of the nucleus and the valence electron are aligned.

Although an atom can assume a multitude of such states, we use only three of them to slow light. In our experiments, when we finish preparing and cooling the atom cloud, every atom is in state 1, its ground state: the valence electron is in its lowest orbit, and its spin is exactly opposite, or anti-aligned, with the nuclear spin. Also, the total magnetism of each atom is anti-aligned with the magnetic field that we use to hold the cloud in place. State 2 is a very similar state, just with the electron and nuclear spins aligned, which raises the atom’s energy a little. State 3 has about 300,000 times more energy than state 2 and is produced by boosting the valence electron up to a larger orbit. Atoms relaxing from state 3 down to state 1 or 2 generate the characteristic yellow glow of sodium streetlights.

The pulse of light that we wish to slow is tuned to the energy difference between states 1 and 3. If we sent a pulse of that light into the cloud without doing any other preparation, the atoms would completely absorb the pulse and jump from state 1 to state 3. After a brief time, the excited atoms would relax by reemitting the light, but at random and in all directions. The cloud would glow bright yellow, but all information about the original pulse would be obliterated.

To prevent this absorption, we use electromagnetically induced transparency, a phenomenon first observed in the early 1990s by Stephen E. Harris’s group at Stanford University. In electromagnetically induced transparency, a laser beam with a carefully chosen frequency shines on the cloud and changes it from being as opaque as a wall to being as clear as glass for light of another specific frequency.

The transparency-inducing beam, or coupling beam, is tuned to the energy difference between states 2 and 3. The atoms, in state 1, cannot absorb this beam. As the light of the probe pulse, tuned to state 3, arrives, the two beams shift the atoms to a quantum superposition of states 1 and 2, meaning that each atom is in both states at once. State 1 alone would absorb the probe light, and state 2 would absorb the coupling beam, each by moving atoms to state 3, which would then emit the light at random. Together, however, the two processes cancel out, like evenly matched competitors in a tug of war—an effect called quantum interference. The superposition state is called a dark state because the atoms in essence cannot see the beams (they remain “in the dark”). The atoms appear transparent to the probe beam because they cannot absorb it in the dark state. Which superposition is dark—what ratio of states 1 and 2 is needed—varies according to the ratio of light in the

Overview / Stopping Light

- Nothing travels faster than light in a vacuum, but even light is slowed down in many media. Scientists have manipulated clouds of atoms with lasers so that pulses of light travel through the clouds at one twenty-millionth of their normal speed—slower than highway traffic.
- A similar technique completely halts the pulses, turning them into a quantum imprint on the atoms. Later, another laser beam converts the frozen pulse back into a moving light pulse with all the properties of the original.
- The process of slowing and stopping light has many research and technological applications.

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coupling and probe beams at each location. But once the system starts in a dark state (in this case, 100 percent coupling beam and 100 percent state 1), it adjusts to remain dark even when the probe beam lights up.

A similar cancellation process makes the refractive index exactly one—like empty space—for probe light tuned precisely to state 3. At very slightly different frequencies, however, the cancellation is less exact and the refractive index changes. A short pulse of light “sniffs out” this variation in the index because a pulse actually contains a small range of frequencies. Each of these frequencies sees a different refractive index and therefore travels at a different velocity. This velocity, that of a continuous beam of one pure frequency, is the phase velocity. The pulse of light is located where all these components are precisely in sync (or, more technically, in phase). In an ordinary medium such as air or water, all the components move at practically the same velocity, and the place where they are in sync—the location of the pulse—also travels at that speed. When the components move with the range of velocities that occurs in the transparent atoms, the place where they are in sync gets shifted progressively farther back; in other words, the pulse is slowed. The velocity of the pulse is called the group velocity, because the pulse consists of a group of beams of different frequencies.

This process differs in a number of important respects from the usual slowing of light by a medium with a refractive index greater than one: the group velocity is slowed, not the phase velocity; the very steep variation of the refractive index, not a large value of the index itself, causes the slowing; and the coupling laser beam has to be on the entire time.

Ultracold Atoms for Freezing Light

The more rapidly the refractive index changes with frequency, the slower the pulse travels. How rapidly the index can change is limited by the Doppler effect: the incessant motion of the atoms in the gas smears out each state across a small range of energies. The Doppler effect is like the change in tone of a siren moving toward or away from you. Imagine the cacophony of tones you would hear if many police cars were racing toward and away from you at various speeds.

My research group uses extremely cold atoms (which move slowly) to minimize this Doppler spreading. Consequently, the energy states are sharply defined, and the frequency range where cancellation occurs can be made narrow. Slow light in room-temperature gases has been obtained by Marlan O. Scully’s group at Texas A&M University, Dmitry Budker’s group at the University of California at Berkeley, and the group at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Mass., led by Ronald L. Walsworth and Mikhail D. Lukin. The use of hot atoms saves these groups from having to produce ultracold atoms, but it limits their ability to slow light.

We chill our sodium atoms with a combination of laser beams, magnetic fields and radio waves. The atoms first emerge from a hot source as an intense beam, traveling about 2,600 kilometers an hour. A laser beam hits the atoms head-on and in a millisecond slows them to 160 kilometers an hour—a deceleration of 70,000 gravities produced by a laser beam that wouldn’t burn your finger. Further laser cooling in an optical molasses—six beams bathing the atoms from all sides—chills the atoms to 50 milli­mols of a degree above absolute zero. In a few seconds we accumulate 10 billion atoms in the molasses. Next we turn off the laser beams, plunging the lab into total darkness, and turn on electromagnets, whose combined field holds the atom cloud like a trap. For 38 seconds we cool the atoms through evaporation, kicking out the hotter atoms and leaving the cooler ones behind. Specially tuned radio waves help to speed the hot atoms on their way. This whole process—from hot beam to cold, trapped atoms—takes place inside a vacuum chamber pumped out to 10–14 (10 quadrillionths) of atmospheric pressure.

When we cool the cloud to about 500 billionths of a degree, it forms a Bose-Einstein condensate, a very odd state of matter in which the several million atoms left after the evaporative cooling behave in a completely synchronized fashion [see “The Coolest Gas in the Universe,” by Graham P. Collins; Scientific American, December 2000]. These ultracold atom clouds, freely suspended in the middle of the vacuum chamber by a magnetic field, are the coldest places in the universe. And
the change in the refractive index, the slower the light travels. A precise frequency and causes an associated sharp variation of its refractive index. The transparency allows properly tuned light to pass through the cloud without being absorbed, and the steeper the change in the refractive index, the slower the light travels.

yet the rest of our experimental setup, within one centimeter of the cloud, is at room temperature. Vacuum-sealed windows on the chamber let us see the atoms directly by eye during laser cooling: a cold atom cloud in optical molasses looks like a little bright sun, five millimeters in diameter. Such easy optical access allows us to massage the atoms with laser beams and make them do exactly what we want.

When our cigar of cold atoms is in place, we illuminate it from the side with the coupling laser. Then we launch a probe pulse along the axis of the cigar. To measure the speed of the light, we do the most direct measurement imaginable: we sit behind the atom cloud with a light detector and wait for the light pulse to come out, to see how long it takes. Immediately after the pulse has gone through, we measure the length of the cloud with yet another laser beam, shone from below to project the cloud’s shadow onto a camera. That length divided by the delay of the pulse gives us the velocity. The delays are typically in the range of microseconds to milliseconds; this might sound short, but it is equivalent to light taking a detour through kilometers of optical fiber wound in a coil.

When we slow a light pulse down by a factor of 20 million, more happens than just a change of speed. At the start our pulse of light is a kilometer long, racing through the air at nearly 300,000 kilometers a second. (Of course, our laboratory’s length is much less than a kilometer, but if we could place our laser that far away, its pulses would be that long in the air.) The pulse’s leading edge crosses the glass window into the vacuum chamber and enters our levitating speck of sodium atoms. Inside this tenuous cloud the light travels at 60 kilometers an hour. A cyclist on a racing bike could overtake such sluggish light.

**Through the Gas, Darkly**

With the front of the light pulse traveling so slowly and its tail still going full tilt through the air, the pulse piles into the gas like a concertina. Its length is compressed by a factor of 20 million to a mere twentieth of a millimeter. You might expect the light’s intensity to increase greatly because the same amount of energy is crammed into a smaller space. This amplification does not happen, however; instead the electromagnetic wave remains at the same intensity. Put another way, in free space the pulse contains 50,000 photons, but the slow pulse contains 1/400 of a photon (the factor of 20 million again). What has happened to all the other photons and their energy? Some of that energy goes into the sodium atoms, but most of it is transferred to the coupling laser beam. We have monitored the coupling laser’s intensity to observe this energy transfer directly.

These transfers of energy also change the states of the sodium atoms where the pulse is passing by. At the front of the pulse the atoms are changed from their original state 1 to a superposition of states 1 and 2, the dark state discussed above. The dark state has the largest proportion of state 2 at the central, most intense part of the pulse. As the rear of the slow pulse leaves a region of atoms, the atoms change back to state 1. The pattern of dark states in the cloud mimics the form of the compressed slow-light pulse and accompanies it through the gas as a wave.

When this wave and the light pulse reach the end of the gas cloud, the light pulse sucks energy back out of the atoms and the coupling beam to dash away through the air at its customary 300,000 kilometers a second, restored to its original kilometer of length.

The velocity of the slow light depends on several parameters. Some of the parameters are fixed once we choose our atom species and which excited states to use, but two of the variables are under our control: the density of the atom cloud and the intensity of the coupling laser beam. Increasing the cloud’s density decreases the light’s speed, but we can push that only so far, in part because very dense clouds leak atoms out of the magnetic trap too rapidly. The pulse speed is also reduced if the coupling laser beam is weaker. Of course, if the coupling laser is

**OPTICAL PROPERTIES** induced in a cloud of atoms by a carefully tuned laser beam are the key to the light-slowing process. A coupling laser beam passing through the cloud makes it transparent to light of a precise frequency and causes an associated sharp variation of its refractive index. The transparency allows properly tuned light to pass through the cloud without being absorbed, and the steeper the change in the refractive index, the slower the light travels.

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**THE AUTHOR**

**LENE VESTERGAARD HAU** is Gordon McKay Professor of Applied Physics and professor of physics at Harvard University and heads the Atom Cooling Group at the Rowland Institute for Science in Cambridge, Mass., where the experiments detailed in this article were performed. She received her Ph.D. in theoretical solid state physics from the University of Århus in Denmark. The author wishes to thank the wonderful Rowland Institute team of Zachary Dutton, Chien Liu, Cyrus H. Behroozi, Brian Busch, Christopher Slowe and Michael Budde, as well as Stephen E. Harris of Stanford University, for an extremely fruitful collaboration.
BLACK HOLE: Slow light drawn into a whirlpool of atoms could simulate phenomena expected in the warped spacetime near black holes.
WHENEVER WE MENTION THE SPEED OF LIGHT in these pages, readers send us questions. Here we try to lay a few perennial puzzles to rest. More are tackled online at www.sciam.com/2001/0701issue/0701hauibox1.html

I read that charged particles traveling faster than light emit Cerenkov radiation—but how can anything go faster than light? Isn't it supposed to be the universal speed limit? This goes to the heart of much confusion about the speed of light. “The speed of light” has two quite distinct meanings. One is “the speed at which light travels,” and that speed varies depending on the medium: fastest in a vacuum, a tiny bit slower in air, two thirds as fast in glass.

The second meaning, the universe’s speed limit, is phrased more carefully as “the speed of light in a vacuum” and is given its own symbol: c. The velocity c seems to be an absolute, unchanging quantity. The speed at which light travels through a vacuum is only one of c’s manifestations, however. We call c the speed of light only because of the historical accident that scientists first encountered c in its role as the velocity of light and other electromagnetic waves. Some physicists advocate renaming c “Einstein’s constant.”

When we distinguish these two speeds of light, the conditions for Cerenkov radiation are no puzzle. In water, light travels at about 0.75 c. Particles can go faster than that through water without breaking the speed limit of 1.00 c.

What is the speed of light?
c is exactly 299,792,458 meters per second.

Exactly? How can it be a whole number?
Some metrological sleight of hand is at work: nowadays the meter is defined as the distance light travels in a vacuum in 1/299,792,458 of a second. Metrologists define the meter that way because doing so results in a quantity that is more precise than the alternatives.

Why is c a speed limit anyway?
This relates to the real importance of c: it defines a fundamental relation between space and time. A distance of 299,792,458 meters is equivalent to a time interval of one second. This is one of the messages of Einstein’s theory of special relativity: space and time are different aspects of a single entity called spacetime.

In spacetime, if one can travel faster than c, one can devise ways to travel through time into the past. Time travel would unleash logical paradoxes of cause and effect, which convinces many physicists that such travel (and even transmission of information faster than c) must be impossible. There are other reasons or clues as well (see our Web site), not least of which is the lack of evidence of any physical object or signal traveling faster than c.

—Graham P. Collins, staff writer and editor

THE SPEED OF LIGHT Q&A

THE PROCESS OF SLOWING and stopping light opens up many interesting experiments. For example, we could send a light pulse through a Bose-Einstein condensate with the light speed adjusted to match the speed of sound in the condensate (around one centimeter a second). Atoms of the condensate should surf along with the light pulse, setting off oscillations of the entire condensate. This would be a completely new way to study superfluid properties of condensates. Condensates can also be produced in a vortex state, wherein the gas rotates, reminiscent of water going down the drain. A pulse of slow light traveling through a vortex would find itself dragged along with the gas—very similar to a phenomenon expected to occur near black holes. With slow light, we can study this and some other black hole phenomena in the laboratory.

Slow light also enables a new kind of nonlinear optics, which occurs, in particular, when one laser beam alters the properties of another beam. Nonlinear optics is a huge field of research, both of fundamental interest and with applications from imaging to telecommunications. Extremely intense beams...
are usually needed to achieve nonlinear optical effects, but with slow light the corresponding phenomena can be produced with a very small number of photons. Such effects could be useful for creating ultrasensitive optical switches.

Another application for slow and stopped light could be quantum computers, in which the usual definite 1’s and 0’s are replaced with quantum superpositions of 1’s and 0’s called qubits. Such computers, if they can be built, would be able to solve certain problems that would take an ordinary computer an enormously long time. Two broad categories of qubits exist: those that stay in one place and interact with one another readily (such as quantum states of atoms) and those that travel rapidly from place to place (photons) but are difficult to make interact in the ways needed in a quantum computer. The slow-light system, by transforming flying photons into stationary dark state patterns and back, provides a robust way to convert between these types of qubits, a process that could be essential for building large-scale quantum computers. We can imagine imprinting two pulses in the same atom cloud, allowing the atoms to interact, and then reading out the result by generating new output light pulses.

Even if frozen light doesn’t prove to be the most convenient and versatile component for building a quantum computer, it has opened up more than enough research applications to keep us—and other groups—busy for many more all-night sessions in the years to come.

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