



# Light Standing Still?

## A Look Back at the Study of Light at Harvard

By Julia Pian

Just as you can get a ticket for going too slow on the highway, one beam of light was actually “pulled over” or stopped by scientists at Harvard.

That beam certainly amazed physicists and non-physicists alike, even though it did not break the cardinal rule of physics that nothing travels faster than 299, 792, 458 meters/second, the speed of light in a vacuum.

A little over ten years ago, in January

of 2001, Dr. Lene Hau of Harvard’s Department of Physics, and Dr. Ron Walsworth at the Harvard-Smithsonian Center for Astrophysics, both

*“I thought, gee, [BECs] is super exciting, and such an interesting state of matter that I want to get my hands on it!”*

published independent results claiming that they had frozen light in its tracks- not a trivial task! Photons do not respond to a simple “sit still!”, but they do slow down as they travel through different materials.

### Background: BECs and Bicycle Speeds

Harvard’s Dr. Lene Vestergaard Hau first started this research after hearing in 1995 about the work of Eric Cornell and Carl Wieman of the University of Colorado, Boulder, and the creation of the first Bose-Einstein Condensate (BEC). In 1924, Albert Einstein and Satyendra Nath Bose predicted a new and weird state of matter that Dr. Hau describes as “a state of matter where you can get millions of atoms to behave in lockstep [or] do exactly the same thing... and I thought, gee, this is

credit: <http://www.epa.gov/region5fields/htm/methods/gps/index.html>

super exciting, and such an interesting state of matter that I want to get my hands on it!” In the 1920s, using the newly formulated theories of quantum mechanics, Bose and Einstein realized that at extremely low temperatures, a group of gaseous atoms would all be at the same quantum level (all their electrons are at the same energy level) and, therefore, identical. In a sense, the group of atoms would become one indistinguishable “super atom,” partly owing to the Heisenberg Uncertainty Principle, which forbids us from being able to pinpoint the exact location of a particle at a certain time.

After creating their own BEC, Dr. Hau’s lab started prodding and poking this substance to see what else it could do. “In the process of probing it with laser beams, we began to think, what if we could send two very particular laser beams with exactly the right wavelength and moving in the right direction, so that we could use one laser beam to manipulate the optical properties of the cloud, such that we could send in another laser beam and slow it down dramatically.” And thus began the quest to stop light.

The speed of light is one of the well-respected properties of the universe, and reducing it significantly, therefore, is not exactly trivial. Dr. Hau’s team first saw evidence of light pulses slowing down as they travel through a BEC in March 1998 (at 4 am in the morning because the experiments often require long, unconventional hours!), and within months, had honed their techniques, so that an airplane could out-fly their beams. As their light slowing technology became more advanced, the pulse speeds diminished

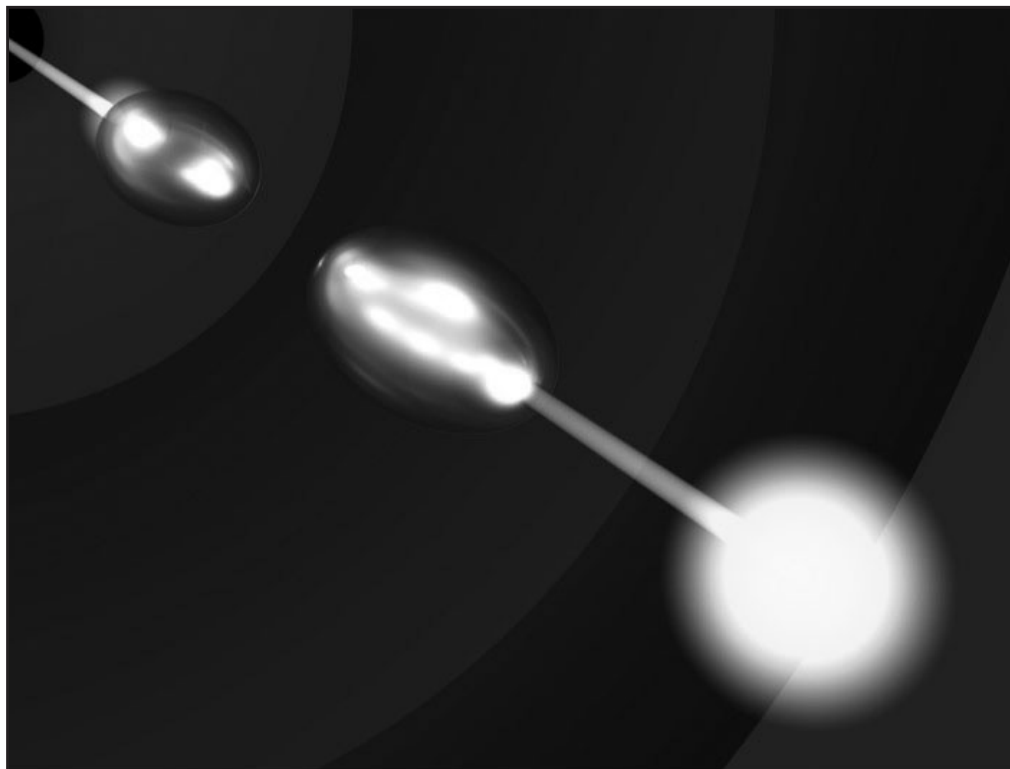
***“Dr. Hau’s team first saw evidence of light pulses slowing down in March 1998 (at 4am in the morning, because the experiments often require long, unconventional hours!), and within months, had honed their techniques, so that an airplane could out-fly their beams.”***



and the technology needed to outpace it became more and more rudimentary. At one point, even a bicyclist could outride it and soon after a baby could crawl faster than their slowed beams. Despite these amazing results, Dr. Hau states that this research was not always smooth sailing: “There are always things that you have to fix, and they seem to come in clumps. One thing will break down and you have to

get it fixed, then another thing, and you just have to keep going. Since we have a lot of equipment in the lab, you have to keep a lot of balls in the air, because if one thing doesn’t work, the whole thing won’t work.... You have to sort of keep up with what isn’t working, and figure out each problem, but when you do get it to be successful, it is definitely worth all the hard work.”

There is a philosophical line between slowing light down and stopping it. Slowing down a light beam shows the ability to control it momentarily, while stopping it suggests that light has been conquered. The ability to stop light is like giving scientists the reigns and, therefore, control over that beam. In the summer of 2000, Dr. Hau and her team observed the first instance of light



◀ **Figure 1.** Two Bose-Einstein Condensates and a light beam “teleporting” them.

being completely stopped in its tracks.

### How Did They Do It?

Even though light is often portrayed as always traveling at a constant 299,792,458 meters/second, when traversing through different materials, light actually slows down, but just by a bit. Even through dense diamond, light still approximately travels at an impressive 1,250,000 meters/second, still many orders of magnitude above air-plane speeds. Thus, to get down to velocities that a human can relate to, Dr. Hau's group had to take advantage of the effects of quantum mechanics and the properties of a Bose-Einstein condensate.

Walking into Dr. Hau's laboratory, you will see carefully-ordered criss-

crossing, yellow laser beams on a huge optics table, called the laser cooling center. Sodium atoms contained in a magnetic field were super-cooled to below a millionth of a degree above absolute zero, creating a Bose-Einstein

condensate of 0.1 millimeters in diameter. Trapped in a vacuum chamber by a magnetic field, the atoms, which look like a tiny bright star, can be seen by scientists through little windows. Since sodium is an alkali metal, its one valence electron's energy state is indicative of the atom's

energy state. Three energy states were used for this experiment: state 1, the ground state, where the valence electron is in the lowest energy state, state 2, with slightly higher energy, and state 3, with about 3,000,000 times more energy in comparison to state 2.

If a laser beam was directed into a

***“Dr. Hau describes it by saying ‘the whole light pulse will compress, like a little concertina, by a factor of a hundred million’ to 0.02mm, ‘so that it fits snugly inside the BEC’.”***

cloud of sodium atoms without the super-cooling preparation, some of the sodium atoms would become excited (moving from state 1 to state 3), then as the atoms descend back to state 1, the cloud would arbitrarily reemit light in every direction. In other words, it would be absorbed and scattered. However, shining another beam of light with a very specific frequency onto the BEC creates electromagnetically induced transparency, turning the opaque cloud as clear as a crystal for light to travel through. The energy state of this laser beam is the difference between states 2 and 3, while the energy state of the

laser beam that is about to be stopped is tuned to the difference between states 1 and 3. Thus, when both beams hit the cloud, through quantum interference, the sodium atoms actually move to a state where they are in both state 1 and 2 at the same time! In this superposition or “dark state” the atoms cannot “see” or absorb the light pulse, and only slow it down.

Once the front end of the light pulse enters the cigar shaped cloud, it begins to slow down, but the back edge of the light pulse (which is nearly a kilometer long in air) is still rushing forward at enormous speeds. Dr. Hau describes it by saying that “the whole light pulse will compress, like a little concertina, by a factor of a hundred million” to 0.02 mm, “so that it fits snugly inside the BEC”. Once the entire light pulse is slowly creeping through the BEC, the coupling laser beam is turned off, and the light pulse stops. In a sense, it turns itself off. However, the information in the original pulse is imprinted on the atoms in the BEC. Dr. Hau's team can even “grab onto the imprint, move it out into free space, photograph it, and

move it back into the condensate.” Once the coupling laser is turned back on, the pulse magically reappears unscathed. Scientists can hold the light still for up to milliseconds (before the

information stored in the BEC starts to degrade).

### Light to Matter and Back: Recent Research

Dr. Hau’s research has not just stopped there. After stopping light in 2001, her team began work on turning a light pulse into a perfect matter copy, with no loss of information. Everyone knows of Einstein’s equation  $E=mc^2$ , which shows that energy and mass can be interconverted, and the imprint that the light has made on the BEC is in a sense the light turned into a mass copy. As Dr. Hau explains, “usually light is very hard to manipulate, but once you have it in matter form, with exactly the same shape properties and content as the original light pulse, you can grab onto it or put it on the shelf [for up to minutes at a time]. When you feel like it, you can turn it back into light and send it on its way. And while you hold onto it, you can actually start massaging the matter copy, changing its shape and therefore its information content.” The changes in information content will be preserved when it is translated back into light. These capabilities present a possibility for computers that use light to transmit information, making processing faster and even more powerful.

In 2007, the cover of *Nature* displayed an illustration with light entering one condensate, and reviving in different condensate, as Dr. Hau describes “a magic trick using quantum mechanics.” In this more recent study by Dr. Hau’s lab, the light was turned into a matter copy in the first condensate, which then traveled to the second condensate, where the light pulse was regenerated and went happily on its way. Current research includes attempts to make the bulky machinery currently required to slow down and manipulate light to nano-scales for use in a myriad of applications.

### Looking into the Future

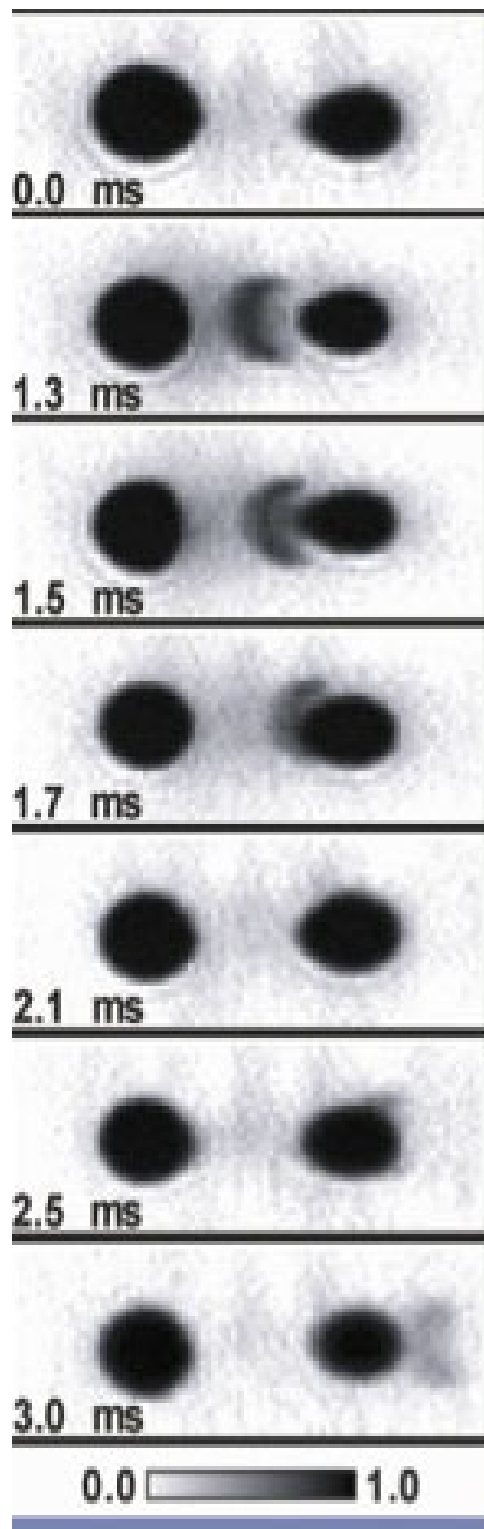
From quantum supercomputers to other possible applications such as ultra-secure cryptography, the applications of this research are endless, and it does not look like Dr. Hau’s research is slowing down either. She never seems to have a shortage of ideas. Dr. Hau attributes this to the process of experimental physics. She states, “a lot of people think experimental physics means sitting alone in a room and once every ten years or so getting an idea, but that’s not what it’s like. Research is working hard in the lab, calculating, and discussing with colleagues. That is how you get all the stuff in your brain that maybe someday will condense in a certain way.... and you will have a new idea.”

Yet, it is more than just the theory that excites Dr. Hau. “One thing is having an idea, and getting it to work in the lab is another thing.” Turning an intangible, almost fantasy-like idea, into real data seems absolutely exhilarating: “You’re sort of dancing right on the edge of what is possible... You know you are the first in history to ever be in this part of nature.” **H**

—Julia Pian ‘15 is a prospective Chemical and Physical Biology concentrator in Stoughton Hall.

### References

1. The National Academy of Sciences. “The Global Positioning System: The Role of Atomic Clocks.” 24 October 2008. <<http://www.beyonddiscovery.org/content/view.page.asp?l=467>>
2. Bajjal, Rahat and Manoj K. Aurora. “GPS: A Military Perspective.” 24 October 2008. <<http://www.gisdevelopment.net/technology/gps/techgp0048.htm>>
3. Holton, W. Conard. “Farming From a New Perspective: Remote Sensing Comes Down to Earth.” *Environmental Health Perspectives*. 108.3 (2000): A130-133.
4. Hub, A. et al. “Real and virtual explorations of the environment and interactive tracking of movable objects for the blind on the basis of tactile-acoustical maps and 3D environment models.” *Disability and Rehabilitation Assistance Technology*. 3.1 (2008): 57-68.
5. Hafner, Katie and Saritha Rai. “Governments Tremble at Google’s Bird’s Eye View.” 24 October 2008. <[http://www.nytimes.com/2005/12/20/technology/20image.html?\\_r=1&sq=governments%20tremble%20at%20google&st=cse&adxnnl-](http://www.nytimes.com/2005/12/20/technology/20image.html?_r=1&sq=governments%20tremble%20at%20google&st=cse&adxnnl-)



▲ Figure 2. Actual images showing the 2 BECs as black dots and the matter copy of the light beam as the boomerang shaped smear.