Mark G. Raizen holds the Sid W. Richardson Foundation Regents Chair in Physics at the University of Texas at Austin, where he also earned his Ph.D. His interests include optical trapping and quantum entanglement. As a toddler, Raizen got to meet physicist Leo Szilard, who was a patient of his father, a cardiologist, and who explained why Maxwell's demons do not violate the laws of thermodynamics.

PHYSICS

DEMONS ENTROPY AND THE QUEST FOR ABSOLUTE ZERO

A 19th-century thought experiment has turned into a real technique for reaching ultralow temperatures, paving the way to new scientific discoveries as well as to useful applications

By Mark G. Raizen

IN BRIEF

Traditional methods for cooling gases to close to absolute zero work only with a few of the elements.

Two novel techniques together can cool down atoms of virtually any element, even some molecules.

One of the techniques, which appears to break the second law of thermodynamics, is a physical realization of a celebrated 1800s thought experiment called Maxwell's demon.

Applications range from studying the properties of elementary particles without expensive accelerators to separating isotopes for their use in medicine and research.

Photograph by Adam Voorhes

S YOU READ THESE WORDS, THE AIR'S MOLECULES ARE ZIPPING around you at 2,000 miles per hour, faster than a speeding bullet, and bombarding you from all sides. Meanwhile the atoms and molecules that make up your body incessantly tumble, vibrate or collide with one another. Nothing in nature is ever perfectly still, and the faster things go, the more energy they carry; the collective energy of atoms and molecules is what we call, and feel as, heat.

Even though total stillness, corresponding to the temperature of absolute zero, is physically impossible, scientists have edged ever closer to that ultimate limit. In such extreme realms, weird quantum effects begin to manifest themselves and to produce new and unusual states of matter. In particular, cooling gaseous clouds of atoms—as opposed to matter in the liquid or solid state—to a small fraction of a degree above absolute zero has enabled researchers to observe matter particles behaving as waves, to create the most precise measuring instruments in history, and to build the most accurate atomic clocks.

The drawback of these atom-cooling techniques is that they are applicable to only a few of the elements in the periodic table, limiting their usefulness. For example, hydrogen, the simplest of all atoms, was for a long time extremely challenging to cool. Now, however, my research group has demonstrated a new cooling method that works on most elements and on many types of molecules as well.

My inspiration: James Clerk Maxwell's Victorian-era thought experiment. This great Scottish physicist theorized the possibility of a "demon" that seemed able to violate the rules of thermodynamics.

The newfound capability will open directions in basic research and lead to a wide range of practical uses. For example, variants on the technique may lead to processes for purifying rare isotopes that have important uses in medicine and in basic research. Another spin-off might be an increase in the precision of nanoscale fabrication methods that are used to make computer chips. On the science side, cooling atoms and molecules may enable researchers to explore the no-man's-zone between quantum physics and ordinary chemistry or to uncover possible differences in behavior between matter and antimatter. And supercooling hydrogen and its isotopes could help small laboratories to answer questions in fundamental physics of the type that have traditionally required huge experiments such as those at particle accelerators.

RACING BULLETS

STOPPING AND MANIPULATING ATOMS and molecules is no easy feat. In a typical experiment, researchers begin by producing a rarefied gas of a certain chemical element by heating up a solid or vaporizing one with a laser. The gas must then be slowed, confined in a vacuum chamber and kept away from its walls.

I started out with a time-honored trick. More than 40 years ago chemists found out that at a pressure of several atmospheres, gas escaping through a small hole into a vacuum undergoes significant cooling as it expands. Remarkably these "supersonic beams" are nearly monoenergetic, meaning that the speeds of molecules will all be very close to the average: for example, if a beam comes out at 2,000 miles per hour, molecules in it will deviate from that speed by at most 20 mph. By comparison, air molecules at room temperature, with an average speed of 2,000 mph, can have speeds anywhere between 0 and 4,000 mph. What that means, from the thermodynamic point of view, is that the beam, despite having a substantial amount of energy, is extremely cold. Think of it this way: an observer traveling with the beam at 2,000 mph would see molecules moving so slow that the beam's temperature would be just one 100th of a degree above absolute zero!

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I realized that if my collaborators and I could slow down and stop such a beam while preserving the small spread in velocity, we could end up with a rather cold bunch of atoms that we could then trap and cool down even further.

To achieve that goal, my group started working with supersonic beams in 2004, together with Uzi Even, a chemist at Tel Aviv University. Our first attempt was to build a rotor with blades moving, at their edges, at half the speed as the supersonic gas beam. We aimed pulses from the beam at the rotor's receding blades in such a way that the beam's velocity would precisely cancel out with that of the blades. When the gas atoms bounced off the rotor, the rotor took all the kinetic energy out of them, just as a receding tennis racket can bring a ball to rest.

That setup, however, was difficult to work with because it required extreme fine-tuning. Robert Hebner, director of the Center for Electromechanics at the University of Texas at Austin, suggested a different design: bounce the gas off the back of a projectile as the projectile races down a coilgun. A coilgun is an experimental weapon that pushes magnetized projectiles out the barrel of a gun with magnetic fields rather than gunpowder. It works by accelerating the bullet through a series of wire coils that have electric current running through them, creating magnetic fields. The bullet, which is essentially a bar magnet, is attracted to the center of the coil it is passing through. An approaching bullet is thus accelerated by attractive forces. Once the bullet passes the center, on the other hand, the forces would start to pull it back and thus slow it down to its original speed. But the current in each coil is switched off precisely at the moment the projectile crosses its center, so that the magnetic forces always push the projectile in the right direction—down the barrel.

I quickly realized that we could apply Hebner's idea but get rid of the bullet altogether. Instead we would use the same principle on the beam itself, though in reverse: rather than accelerating a bullet, the coils of the gun would act in this case directly on the gas molecules, bringing them to rest [*see box on opposite page*]. The trick is possible because most atoms have at least a small amount of magnetism, and all do when their electrons are put in an excited state. Many types of molecules are magnetic, too.

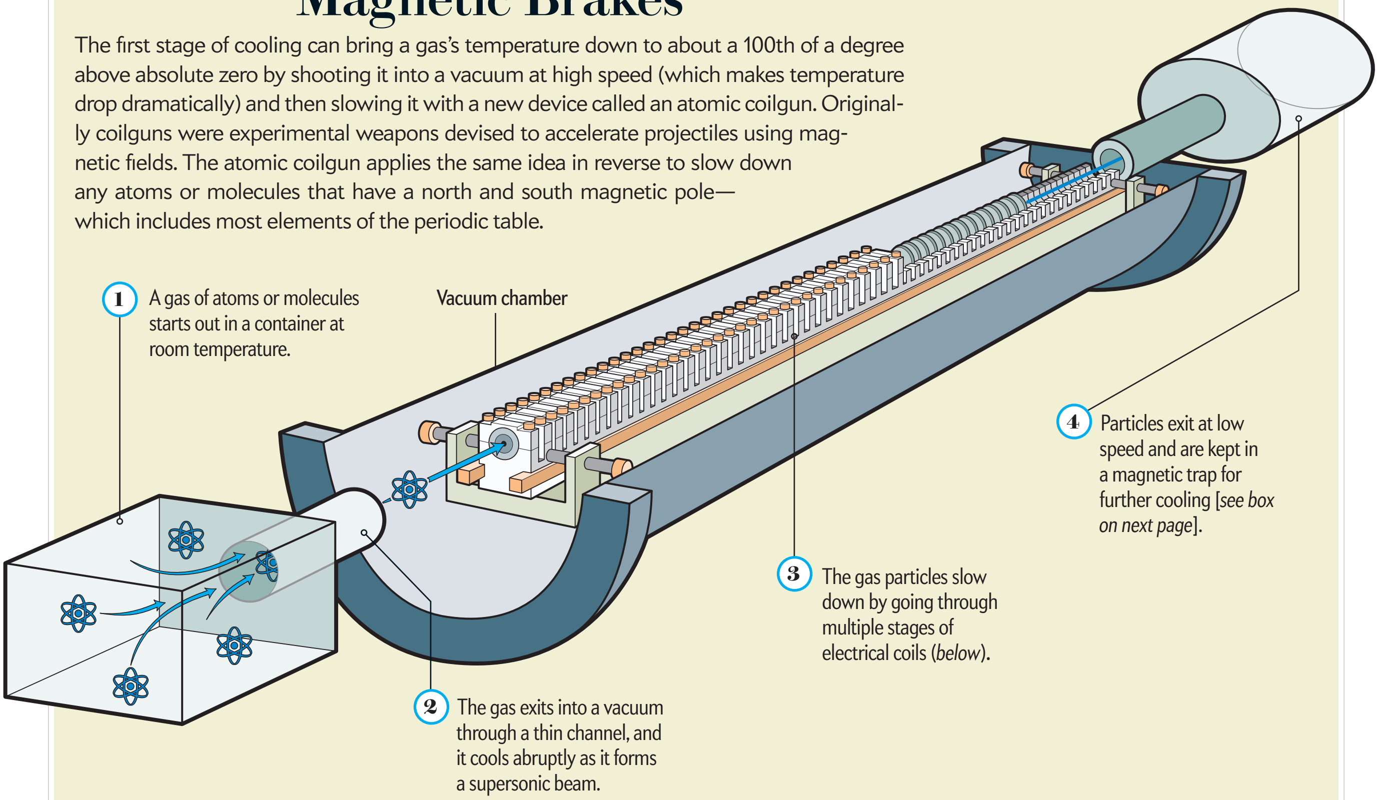
We built the new device and tested it first on excited neon atoms and then on oxygen molecules. We succeeded in stopping both species. Unbeknownst to us, a group working in Zurich led by Frederic Merkt independently developed the same idea and succeeded in stopping atomic hydrogen at roughly the same time we conducted our own experiments. Several groups around the world have now built their own atomic coilguns, which are ultimately very simple and robust devices, based on ordinary copper wire, off-the shelf capacitors and transistors.

Once we succeeded in stopping atoms in this way, it was relatively straightforward to trap them in static magnetic fields. The more difficult problem was to find a way to cool them further. Although 0.01 kelvin (one 100th of a degree above absolute zero) sounds chilly, it is still very far from the limits reached by other techniques. We needed to find a way to go lower.

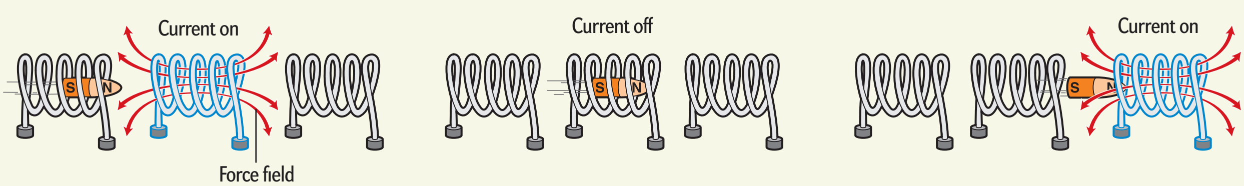
STAGE ONE OF COOLING

Magnetic Brakes

The first stage of cooling can bring a gas's temperature down to about a 100th of a degree above absolute zero by shooting it into a vacuum at high speed (which makes temperature drop dramatically) and then slowing it with a new device called an atomic coilgun. Originally coilguns were experimental weapons devised to accelerate projectiles using magnetic fields. The atomic coilgun applies the same idea in reverse to slow down any atoms or molecules that have a north and south magnetic pole—which includes most elements of the periodic table.



How the Reverse Coilgun Works



1 Current in a coil generates magnetic forces that push a particle (bullet) away from the coil. An approaching particle thus slows down.

2 When the particle reaches the center of the coil, the current shuts off: otherwise, the forces on the exiting side would push the particle back to its original speed.

3 The particle moves toward the next coil, and the process repeats, reducing the particle's speed at each stage.

ONE-WAY ROADS

I WAS THINKING ABOUT general cooling methods well before anyone thought about atomic coilguns, but for a long time I did not see a solution. The technique of laser cooling, which was invented in the 1980s, has been extremely successful—resulting in the creation of a state of matter called Bose-Einstein condensates and in the award of two Nobel Prizes in Physics in 1997 and 2001. But the range of applicability of laser cooling is mostly limited to the atoms in the first column of the periodic table, such as sodium or potassium, because those are easy to switch between a ground state and a single excited state, as required by the technique. Another method I considered was evaporative cooling, which relies on skimming off the hot atoms, leaving the cooler ones behind (the same principle by which sweat cools us off as it evaporates from our skin). But without the aid of laser cooling, it is very hard to get to high-enough density to kick off evaporation in the first place.

In February 2004 I visited Princeton University and talked with Nathaniel J. Fisch, a plasma physicist. He told me about an idea he had just developed: how to drive an electric current of electrons in a plasma—a gas of electrons and positive ions—with a scheme that causes electrons to go in one direction and not the other. I wondered if we could accomplish something similar with atoms or molecules: build a "gate" that lets atoms through in one direction but not the other.

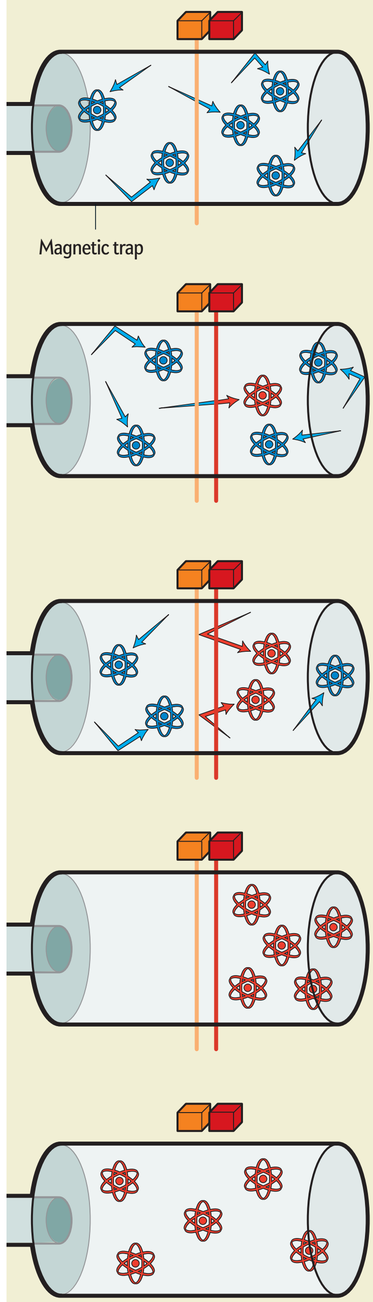
Leaving aside for a moment the technical issue of how to actually build a one-way gate, let me first explain why such a device might help cool down a gas. The first step would be to reduce the

Illustration by Brown Bird Design

STAGE TWO OF COOLING

Devilishly Cool

After an atomic coilgun or some other device has cooled a gas to hundredths of a degree above absolute zero, the serious freeze can begin, down to millionths of a degree or lower. The new technique of single-photon cooling achieves that feat using a one-way gate inspired by a 19th-century thought experiment. The idea is to first let the gate concentrate atoms into a smaller volume (but without raising their temperature) and then allow them to expand to the original volume (which brings their temperature down).



1 Atoms in a given initial state (*blue*) are held in a magnetic trap. A laser that affects those atoms only when they are in a second state is switched on (*orange*).

2 A second laser beam (*red*) switches atoms from their blue state to a second stable state (*red atom*) when they hit it.

3 Atoms in the red state bounce back when they hit the orange laser and so are forced to stay on the trap's right side.

4 All atoms eventually cross the second laser, turning red and ending up on the right side. They are at the same temperature as they started but in a smaller volume.

5 The atoms are allowed to slowly expand back to their original volume. As the gas expands, it cools down.

volume of the gas without raising its temperature. Suppose a gate separates a container into two volumes. Gas atoms bounce around the container randomly and sooner or later end up flying toward the gate. If the gate lets them through in only one direction, say, from left to right, eventually all atoms will concentrate on the right side of the container. Crucially the atoms' velocities do not change in the process, so the gas will be at the same temperature at which it started. (Thermodynamically this procedure is completely different from compressing the gas into the right half of the volume, which would accelerate the atoms and thus raise temperature.)

The second step would be to let the gas expand back to its original volume. When a gas expands, its temperature decreases, which is why spray cans get cold during use. So the end result would be a gas with the original volume but lower temperature.

The problem that long befuddled physicists is that such atom-sorting gates would seem to violate the laws of physics. In its compressed state, the gas has lower entropy, which is a measure of the amount of disorder in a system. But according to the second law of thermodynamics, it is impossible to lower the entropy of a system without expending energy and producing more entropy elsewhere.

This paradox has been a topic of controversy ever since James Clerk Maxwell's thought experiment in 1871, in which an "intelligent being with deft hands" could see the coming and going of particles and open or close a gate appropriately. This hypothetical creature became known as Maxwell's demon and appeared to violate the second law of thermodynamics because it could lower the entropy of the gas while expending a negligible amount of energy. After many years, in 1929, Leo Szilard resolved the paradox. He proposed that the demon collects information every time that the trap door is opened. This information, he argued, carries entropy, which exactly balances the entropy decrease of the gas, thereby "saving" the second law. (Szilard was ahead of his time: in later decades the concept that information has real physical meaning arguably kicked off modern information science.)

All thinking around Maxwell's dilemma, including Szilard's solution, was purely speculative, and for many decades it seemed destined to stay that way. My colleagues and I, however, created the first physical realization of Maxwell's thought experiment the way Maxwell thought it up. (Other recent experiments have done something conceptually similar but with nanomachines rather than gates for a gas.) And we used it to cool atoms to temperatures as low as 15 millionths of a kelvin.

As we shall see, the device we built clarifies how Maxwell's demon can exist in practice, as well as why Szilard's insight—that information plays a crucial role—was correct.

For the one-way gate to work, I reasoned, the atoms in the gas must have two different states (possible configurations of orbiting electrons) that are both of low energy and thus stable. Let us call the two states blue and red. The atoms are suspended in a container that is cut across the middle by a laser beam. The beam is tuned to a wavelength that makes red atoms bounce back when they approach it, so that it acts in essence as a closed gate. Initially all atoms are blue and thus can fly through the laser barrier unimpeded. But just to the right of the barrier beam, atoms are hit by a second laser, this one tuned so that atoms turn from blue to red by scattering a single photon. Now the atoms, being red, are repelled by the barrier beam and thus cannot go through the gate and back to the left side. Eventually all the atoms gather up on the right side, and the left side remains empty.

Illustration by Brown Bird Design

We first demonstrated our gate with atomic rubidium in early 2008. We called our method single-photon cooling to distinguish it from the earlier laser cooling, which required many photons to cool each atom.

Single-photon cooling demonstrates the idea of Maxwell's demon, a being that appears to violate the second law of thermodynamics.

Meanwhile, unbeknownst to me, Gonzalo Muga of the University of Bilbao in Spain, together with his collaborator Andreas Ruschhaupt (now at Leibniz University in Hannover, Germany), independently developed a similar concept. Since then, Muga, Ruschhaupt and I have worked out some of the theoretical aspects of the gate. In a joint paper that appeared in 2006, we pointed out that when an atom scatters one photon, the photon carries away with it information about that atom—and thus a tiny quantum of entropy. Moreover, whereas the original photon was part of an orderly train of photons (the laser beam), the scattered photons go off in random directions. The photons thus become more disordered, and we showed that the corresponding increase in the entropy of the light exactly balanced the entropy reduction of the atoms because they get confined by the one-way gate. Therefore, single-photon cooling works as a Maxwell demon in the very sense envisioned by Leo Szilard in 1929. The demon, in this case, is particularly simple and efficient: a laser beam that induces an irreversible process by scattering a single photon. Such a demon is certainly neither an intelligent being nor a computer and does not need to make decisions based on the information coming from the atoms. The fact that the information is available and can in principle be collected is enough.

FRONTIERS OF TRAPPING AND COOLING

THE CONTROL OF ATOMIC and molecular motion opens new directions in science. Chemists have long dreamed of trapping and cooling molecules to study chemical reactions in the quantum regime. The coilgun works on any magnetic molecule and complements a method that uses electric rather than magnetic forces to slow down any molecule that is electrically polarized. If the molecules are small enough, single-photon cooling should then be able to bring temperatures down low enough that quantum phenomena start to dominate. For example, molecules turn into stretched-out waves that can chemically react over much larger distances than usual and with no need for the kinetic energy that fuels ordinary reactions. Several groups are now pursuing this direction.

Another major advantage of single-photon cooling is that it works on hydrogen—and on its isotopes deuterium (with a neutron in addition to the single proton in the nucleus) and tritium (with two neutrons). In the late 1990s Dan Kleppner and Thomas J. Greytak of the Massachusetts Institute of Technology were able, through heroic efforts, to trap and cool hydrogen using cryogenic methods and evaporative cooling, but they never did the same with the other isotopes. Further progress hinged on new methods to trap and cool hydrogen isotopes in a relatively simple apparatus. Single-photon cooling is perfectly suited to trapping and cooling of all three isotopes of hydrogen. One goal will be to push the current limits of ultrahigh-precision spectroscopy, another important application of cool atoms.

Trapping and cooling of tritium may make it possible to measure the mass of neutrinos, the most abundant of the known elementary particles in the universe, and thus to better understand the particles' gravitational effects on the evolution of the cosmos. Tritium is radioactive, and it transmutes into helium 3 when one of its neutrons decays into a proton, an electron and an antineutrino, the antimatter counterpart of a neutrino. By measuring the energy of the electron, which shoots out as beta radiation, physicists could determine the energy that went missing with the antineutrino—which would fly through the apparatus undetected—and thus the antineutrino's mass; physicists expect the mass of neutrinos to be the same as that of antineutrinos.

The same methods will also work for trapping and cooling antihydrogen, the antimatter equivalent of hydrogen. Antihydrogen has only recently been created at CERN, the particle physics lab near Geneva, and is extremely delicate to handle because antimatter vanishes into a flash of energy as soon as it comes into contact with matter. In this case, the supersonic beam method cannot be used as the starting point. Instead a beam of antihydrogen could be generated by launching antiprotons through a positron cloud and then stopped and cooled with our Maxwell demon. Experiments with antihydrogen will be able to answer the simple question: Does antimatter fall the same way as matter? In other words, does gravity act the same way on all objects of the same mass?

The new techniques of atomic coilgun and single-photon cooling could also have important practical applications. Isotopes from most of the periodic table of elements are still separated using a device called a calutron, invented by Ernest Lawrence during the Manhattan Project. Calutrons separate the isotopes, which have slightly different masses, by an electric field, essentially like a large mass spectrometer. The only active calutron program right now is in Russia and is quite inefficient. A Maxwell demon concept similar to the one that works in cooling could be used to separate isotopes in a beam and would be more efficient than calutrons. This method can produce small quantities of isotopes, such as calcium 48 or ytterbium 168, that are relevant to medicine and basic research but poses no risk for nuclear proliferation because it is practical only for isolating very small amounts of an isotope.

Another spin-off we are pursuing is to build structures on the nanometer scale. Instead of using magnetic fields to slow atoms down, one could let the fields focus atom beams like a lens focuses light, but with a resolution of just one nanometer or better. Such beams could then deposit atoms to create smaller details than is now possible with optical lithography, the golden standard of computer-chip fabrication. The ability to create nanoscale structures in this bottom-up fashion, rather than by the top-down approaches that are more common in nanoscience, will start a new field that I call atomoscience.

Absolute zero may be as unattainable as ever, but there is still much to be discovered—and to be gained—on the path that leads there. SA

MORE TO EXPLORE

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