These reservations qualify as quibbles. Without a doubt, Rupar *et al.* have created a nearly naked germanium(II) dication, a species for which there is no precedent in nonmetallic inorganic chemistry. It may have interesting synthetic applications, as a template for adding two to four groups to germanium. Germanium-73 nuclear magnetic resonance measurements could clarify to what extent germanium is free. Finally, the successful isolation of this species suggests that it may be possible to prepare other unprecedented cations from groups 13 to 17—such as Ga$^+$, Si^{2+}, P^{3+}, As^{3+}, and Sb^{3+}—by imprisonment.

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PHYSICS

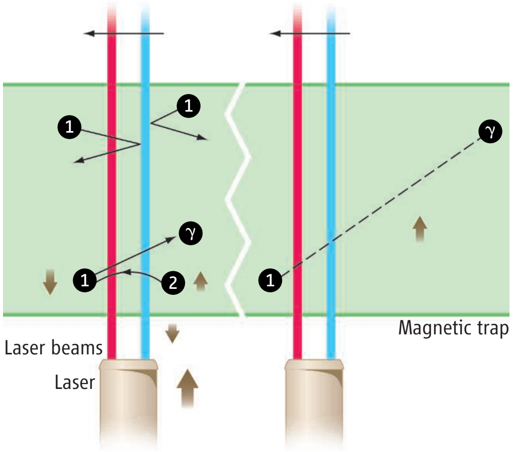
Reflections on a Wall of Light

Single-photon cooling of atoms offers a rare view of a real-life Maxwell's demon.

P.-M. Binder

Optical traps allow atoms to be cooled to ultralow temperatures, where the atoms can form exotic quantum states of matter. Studies to date have, however, been mostly confined to half a dozen or so atomic systems. The recently reported cooling of atoms (*1*) with a one-way wall of light (*2*, *3*) now provides the opportunity to experiment with over 80% of the elements in the periodic table at temperatures of just a few microkelvin. In addition, these selective barriers that allow the trapping of cold atoms are also practical realizations of a familiar mythical being that has accompanied physicists for well over a century: Maxwell's demon. My aim here is to discuss the role played by entropy and information in this particular cooling technique. I will look in turn at the wall, the Maxwell demon (in general), and then both.

In the new method, the atoms are first slowed and trapped magnetically (*4*), creating a tilted potential for the atoms (see the figure, green area). The one-way wall is then implemented by moving two laser beam sheets, tuned to different frequencies (red and blue in the figure), across the magnetic trap. The frequencies are carefully chosen so that one beam acts as a repulsive barrier for atoms in one state ("1") and as an attractive well for atoms in another state ("2"). Low-energy atoms in state 2 go right through the approaching wall and then encounter the second beam that induces an irreversible transition from state 2 to 1, emitting a single photon in the process (see the figure, left panel). With this approach, the captured atoms in state 1 can be gently shepherded to the center of the trap by the wall, where they can be contained for some time.



Reflectively trapped. Green: magnetic trap. Red and blue: laser beam sheets that form the wall. Left of the wall: optical trap. **(Left)** Two atoms in state 1 reflect off the left-moving wall (upper part); a slow atom gets trapped, transitions from state 2 to 1, and emits a photon γ (middle part). The laser increases the net entropy of the universe as illustrated by the relative size of the arrows (bottom part). **(Right)** As the trapped atom and the emitted photon move apart, decoherence increases the total entropy, and the Second Law is safe (once again).

Demons were introduced by James Clerk Maxwell in 1871 to help illustrate the statistical nature of the Second Law of Thermodynamics, which forbids the spontaneous appearance of temperature gradients in a body at equilibrium or the full conversion of microscopic internal energy into organized work. Alternatively, the law can be stated in terms of the entropy of a closed system, which must never spontaneously decrease. Maxwell's nimble-fingered creatures that try to defeat the Second Law by sorting fast and slow gas atoms into two compartments have been analyzed in depth by physicists and philosophers. Arguments over what exactly happens to demons and the environment as the entropy of the gas decreases in apparent violation of the Second Law have helped sharpen our understanding of the crucial concepts of measurement and information. One can attribute to Leo Szilard the discovery of the bit, the unit of information, as part of his 1929 Maxwell's demon paper (*5*).

The generally accepted solution to the missing entropy problem, which arises in the above scenario of ordering the gas atoms, came in two steps. Following Szilard's ideas, it was believed that in the process of measuring the gas atoms as they were being manipulated by the demons, the demons acquired information that somehow offset the entropy decrease of the atoms, thus rescuing the Second Law. But in subsequent work in the 1980s, Charles Bennett (*6*) invoked earlier work of Rolf Landauer (*7*) to argue that any decrease in the entropy of the universe caused by the sorting of atoms will not be regained by the demon while measuring the atom, a possibly reversible process. This is so because atoms and demons become highly correlated and their joint entropy is about the same as their individual entropy. Instead, entropy increases later when the demon's memory of the measurement is erased as the demon returns to its "initial state" and becomes ready for another measurement. A volume by Leff and Rex (*8*) contains most of the work described in these two paragraphs.

Expanding on an existing entropy analysis of the cooling process (*9*), the following picture emerges: Each slow atom being trapped emits a photon at the light wall ("measure-

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ment"); atom-photon pairs are highly correlated, so the photons do not add to the overall entropy. As atoms are collected at the center of the trap, their entropy decreases. The corresponding entropy increase that saves the Second Law does not happen right away but rather as atoms and photons become uncorrelated (*10*) when they drift apart and interact with their surroundings (see the figure, right panel), especially through absorption and scattering of the photons ("erasure"). Note how closely this recapitulates the century-long discovery of the original solution.

There is an additional source of irreversibility not present in the familiar rigid container habitat of the demon. The walls of the optical trap come from a (macroscopic) laser unit, which generates entropy: As photons are collected into a highly organized beam, their entropy is lowered (*11*), but this is more than offset by the laser warming up and transferring energy to its surroundings (see bottom of left panel).

Single-photon cooling of atoms is still being perfected and will extend our ability to probe into the details of the physical world (*1*). A wonderful bonus from this quantum optics experiment is the opportunity to observe a real-life Maxwell's demon in action and to be able to follow the intricate flows of information and entropy in a tangible laboratory setting.

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ASTRONOMY

Exoplanets—Seeing Is Believing

Direct observations have been made of the infrared and optical signatures of planets orbiting distant stars.

Mark S. Marley

The bonanza of extrasolar planet discoveries, more than 300 at last count, has been enabled mainly by two indirect methods—radial-velocity surveys, which detect the motion of the star induced by its orbiting partner, and searches for planets that transit their primary stars. Both methods can reveal the architecture of planetary systems (masses and orbits), and the transiting planets also yield a second harvest (radii, densities, and atmospheric properties inferred partly from absorption of the star's light). Transit characterization methods depend upon proximity of the target planet to the primary star and so far tell us nothing about planets at large orbital separations. The holy grail in planet detection has thus been direct imaging because any planet spatially separated from its primary star is amenable to follow-up characterization. Although there have been previous claims of such detections (*1*, *2*), we ultimately know a planetary system when we see it. Thanks to two papers in this issue—by Kalas *et al*. on page 1345 (*3*) and Marois *et al*. on page 1348 (*4*)—we now have compelling images of the glow of faint planetary companions—not only adjacent to but clearly orbiting stars. Kalas *et al.* present optical Hubble Space Telescope images of what is likely to be a planet with a mass a few times that of Jupiter orbiting the famous bright A star Fomalhaut. Marois *et al.* present a series of infrared images of three giant planets orbiting the A-type star HR 8799 in the constellation Pegasus. The planets (see the figure) are seen in nearly face-on, circular orbits spaced not unlike those of the solar system's giants at larger scale.

Direct imaging of planets is eminently challenging, particularly for ground-based telescopes observing through the blurring effects of the atmosphere, as faint planets are lost in the scattered and diffracted glare of their primary stars. The tools required for planet-imaging searches include adaptive optics techniques, which correct for the blurring of the atmosphere, and coronagraphs, which block out most of the star's light (a technique developed to study the Sun's corona).

Earlier mileposts on the road to images of planets orbiting stars have included the brown dwarf Gliese 229 B (*5*), which orbits an M star, and the several–Jupiter-mass object 2MASS 1207 B (*1*), which orbits a brown dwarf (see the figure). Neither of these low-mass objects nor other contenders fits the planet profile. Gliese 299 B is massive enough to fuse deuterium, which requires a mass greater than about 13 times Jupiter's mass (M_{Jup}) (*6*), and the object that 2MASS 1207 B orbits is not a star—its mass is less than ~75 M_{Jup}, the minimum required to permit fusion of hydrogen to helium (*7*).

The systems studied by Marois *et al.* and by Kalas *et al.* are notable for their similarities. Dusty debris disks, presumably arising from collisions of planetesimals, and perhaps shepherded by the new planets, surround both stars. A similar disk is likely present in our own solar system (*8*). The primary stars in both systems are younger, brighter, warmer, and more massive than the Sun. Although main-sequence A stars are generally not amenable to radial-velocity planet searches, more than a dozen giant planets have been detected by such surveys around evolved A-type stars, and trends suggest that the likelihood of a giant planetary companion increases with stellar mass (*9*).

Although images of faint companions orbiting their primary stars are captivating, their masses must be inferred from their brightness. Unlike stars, giant planets fade as they radiate away the heat of their formation. Thus, estimates of the masses of these planets depend upon how bright and how old they are. Marois *et al.* constrain the total luminosity of each companion to HR 8799 by combining images taken in several different spectral bandpasses, each of which covers a limited range of wavelengths in the infrared. They then compare the luminosities with theoretical models for giant-planet evolution, assuming an estimated stellar age of 30 to 160 million years, and conclude that all three objects have masses well below the ~13 M_{Jup} planet threshold. However, the evolution models at these ages can be sensitive to assumed initial conditions (*10*). Higher-resolution near-infrared spectra of the planets and long-term astrometric measurements of their orbits will ultimately refine their masses. Nevertheless, the multiple objects, faint luminosities, young ages, small companion-to-primary mass ratios, circular, well-spaced

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