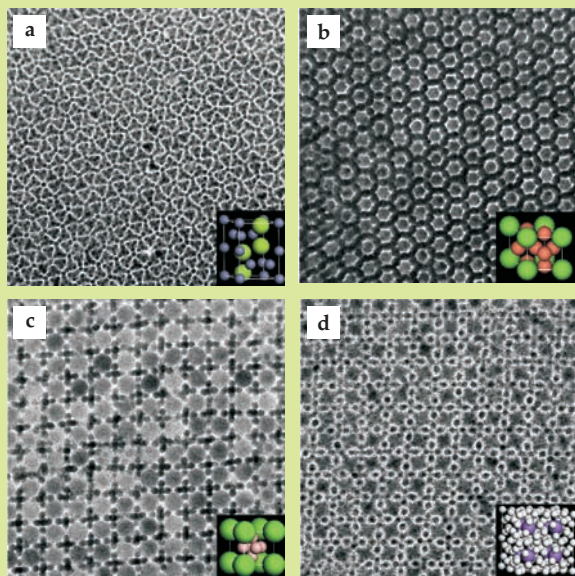




**Figure 2. Diverse structures** are formed spontaneously by particles of different materials, radii, and stoichiometries. (a) 6.2 nm PbSe, 3.0 nm Pd, 1:2. (b) 7.2 nm PbSe, 5.0 nm Au, 1:5. (c) 5.8 nm PbSe, 3.0 nm Pd, 1:6. (d) 7.2 nm PbSe, 4.2 nm Ag, 1:13. Insets show modeled unit cells. (Adapted from ref. 2.)

ing particles whose sizes are comparable to the wavelength of light. Finding optimum structures is paramount.

Murray, Talapin, and their collaborators are interested in electronic applications. They want to combine two different types of functional nanoparticles into so-called binary nanoparticle superlattices (BNSLs). The goal is a material whose properties arise not only from the two types of constituent but also from how the two types interact.

As a first step, Murray and Talapin's group sought to crystallize BNSLs, though not necessarily functional ones. Their nanoparticles ranged in electrical resistance from metals, through semiconductors, to insulators and in size from 3 to 10 nm.

Like the Utrecht microspheres, IBM nanoparticles acquire opposite and modest charges, thanks to a judicious choice of solvent and additives. And, as figure 2 shows, the nanoparticles also form a variety of familiar and unfamiliar structures, including  $AB_{13}$ .

Quantifying the stability of BNSLs is more difficult than for crystals of

micron-sized particles. The attractive electrostatic forces in the Utrecht and IBM colloids may serve to hasten arrival and avoid detours to unwanted phases.

## Goals and applications

A key goal in photonics is the development of efficient and practical bandgap materials that transmit light in a narrow wavelength range through circuits without loss. To work, a photonic bandgap material must be structured on the same scale as the wavelength of light. That scale is easy to achieve with colloidal crystals.

But the right scale isn't enough. The best light-steering performance comes from materials with the most symmetric Brillouin zones, which, in turn come from structures of high point-group symmetry. Close-packed structures have threefold symmetries. But diamond has fourfold symmetry and quasicrystals have five and higher.

High symmetries are tricky to realize. Diamond's structure arises from carbon's directional—that is, nonspherically symmetric—covalent bonds, and

quasicrystals form in a race against the usually more stable normal crystal.

Still, given the tweaking possible—including ternary mixtures and selectively dissolving or sintering one species—van Blaaderen is optimistic. Better photonic bandgap materials, besides improving photonic circuitry, would also boost the efficiency of laser cavities by blocking access to transitions that don't lase.

In the case of BNSLs, the role of structure is to mediate whatever interaction the two species have that underlies the material's function and *raison d'être*. One interaction that could lead to novel materials is spin exchange.

Ferromagnetic materials come in two types: hard magnets, which have low, difficult-to-reorient moments, and soft magnets, which have high, easy-to-reorient moments. Hard magnets, like the rare-earth-based  $Nd_2Fe_{14}B$ , are used to store data. Soft magnets, like permalloy, are used in electric motors and antennas.

A third type of magnet, one whose moment is high and difficult to reorient, is conceivable. To realize it, one could create a BNSL of magnetically hard and soft nanoparticles. Spin exchange, so the theory goes, would tie the high moment of the softs to the high coercivity of the hards.

Charles Day

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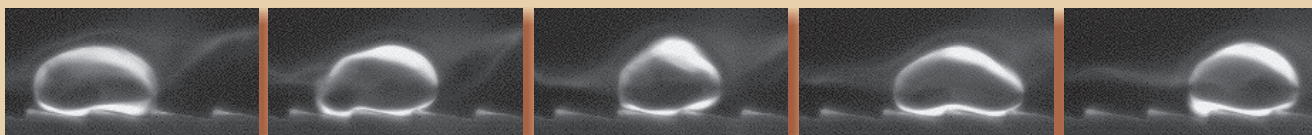
# Drops of liquid exhibit surprising self-propulsion on ratcheted surfaces

Cooks use the Leidenfrost effect to see when skillets are hot enough. Some day it may serve to keep microprocessor arrays cool.

The self-winding wristwatch provides a familiar example of a ratchet. An internal mechanism that's asymmetric with respect to clockwise and counterclockwise converts the energy imparted by random wrist motion into purpose-

ful winding of the clockwork. More generally, a ratchet is a kind of rectifier—macroscopic or microscopic—that forces the otherwise random thermal or mechanical motion of a system that's out of equilibrium into a specific

direction by means of an asymmetric potential. Microscopic ratchets called Brownian motors are thought to be important for motion in biological systems (see the article by Dean Astumian and Peter Hänggi in *PHYSICS TODAY*,



**Figure 1. Self-propulsion of a droplet** of the refrigerant R134a along a ratcheted brass surface with shallow saw teeth 1.5 mm long and 0.3 mm high. These successive video frames 16 milliseconds apart indicate a velocity of about 4 cm/s to the right. At room temperature (48 °C above the refrigerant's boiling point) the brass is hot enough to be in the Leidenfrost regime, where the droplet is levitated above the surface and insulated by a layer of its own vapor a few microns thick. (A video is available at ref. 3.)

November 2002, page 33).

Condensed matter physicist Heiner Linke at the University of Oregon concerns himself primarily with quantum ratchets in low-dimensional semiconductor heterostructures, where the goal is to force the random motion of electrons into a particular direction.<sup>1</sup> But his group's latest paper,<sup>2</sup> which grew out of a casual project he suggested to an undergraduate summer intern a few years ago, is about thoroughly classical, macroscopic, and—dare one say it—entertaining ratchets. Beyond amusement, however, the Oregon group's new ratchets may prove to have technologically important applications.

The ratchets in question are shallow grooves of saw-tooth profile, 1–2 mm wide, machined into the surfaces of brass plates about 20 cm long. When such a surface is made hot enough, Linke and company find, millimeter-size droplets of liquid dripped onto the ratchet surface don't scurry off in random directions as they would when a cook tests the temperature of a hot skillet with a few drops of water. Instead they acquire a speed of about 5 cm/s in the direction dictated by the ratchet's asymmetry (see figure 1). They do this even when they are given an initial velocity in the opposite direction or when the experimenters tilt the ratcheted surface from the horizontal to inhibit their motion. And the droplets have been seen to keep up the directed terminal velocity for distances as long as a meter.

Captured in the video stills of figure 1, the droplets may seem to creep along stodgily amoebalike. But in the real-time videos available on Linke's website, one sees them moving along at a surprising clip.<sup>3</sup>

## The Leidenfrost regime

How hot does the ratcheted surface have to be to accelerate liquid droplets to such impressive di-

rected speeds? That depends on the so-called Leidenfrost temperature of the liquid and the surface. The 18th-century German scientist Johann Leidenfrost discovered that when a liquid is brought into contact with a surface significantly hotter than its boiling temperature, a cushion of its vapor insulates and levitates it above the hot surface. At temperatures between the boiling point and the Leidenfrost point, droplets or thin layers of liquid rapidly boil away. But in the Leidenfrost regime, the insulated droplets evaporate rather slowly without actually boiling.

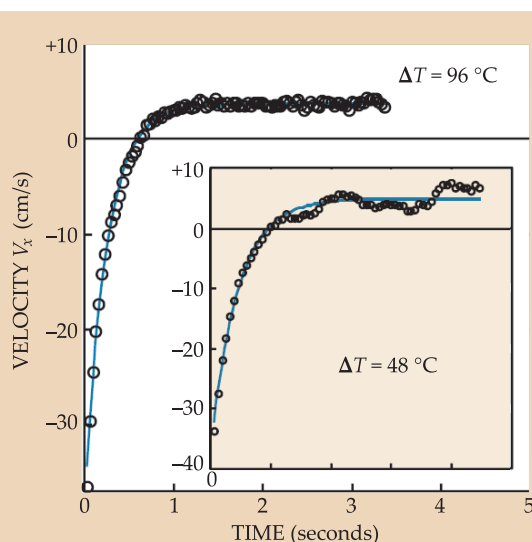
That's the regime in which the Oregon group demonstrated its ratchet effect for a variety of liquids, including water, liquid nitrogen, ethanol, and a flu-

orocarbon refrigerant called R134a. For water on clean brass, the Leidenfrost point  $T_L$  is about 200 °C. But for R134a, whose boiling point is –26 °C, the Leidenfrost point is just about room temperature. Figure 2 shows the acceleration of R134a droplets on the brass ratchet of figure 1 at two different temperatures above  $T_L$ . The droplets are given initial velocities of 35 cm/s in the direction (–x) opposite to the acceleration produced by the ratchet. Their rapid deceleration and then reversal during the first second corresponds to a roughly constant ratchet-induced acceleration of 20 cm/s<sup>2</sup> in the +x direction, damped by a drag force proportional to speed. The net result is a terminal velocity of about 5 cm/s in the +x direction. With the brass ratchet heated above 250 °C, the results for water droplets are much the same.

Liquid droplets have long been known to move on surfaces as a result of surface-tension imbalances due to horizontal thermal, chemical, or electrical gradients. But because all those cases involve high friction due to wetting contact with the surface, speeds have never exceeded a few millimeters per second in the absence of added power. Furthermore, because one quickly runs out of accelerating gradient, total displacements are limited in those cases to a few centimeters.

## A model

In the Oregon Leidenfrost experiment, the only thermal gradient is normal to the brass plate. The group proposes an explanatory model that reproduces its experimental results quite well over a considerable range of temperatures and droplet sizes. When straddling one or more ratchet points in the Leidenfrost regime, the lower surface of a droplet has both convex and concave patches as it sits on its vapor cushion (see figure 3). The difference between the droplet's internal pressure and the pressure of the vapor



**Figure 2. Velocity evolution** of R134a droplets, with the ratcheted brass surface of figure 1 at 96 °C and 48 °C (inset) above the liquid's boiling point. Each droplet was given an initial velocity of 35 cm/s in the direction (–x) opposite to the ratchet's propulsion direction. The fitted curves correspond to constant acceleration of about 20 cm/s<sup>2</sup> in the +x direction, damped by a drag force proportional to speed. Both temperatures are above the Leidenfrost point for R134a on brass, but the higher temperature yields a smoother progression to the expected terminal velocity. (Adapted from ref. 2.)

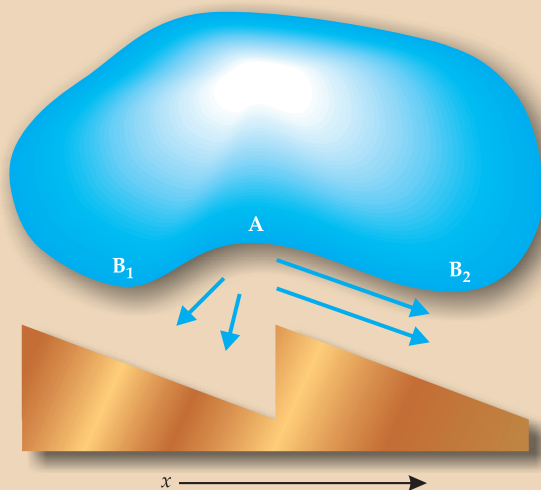
near a point on the lower surface is well approximated by  $\gamma/R$ , where  $\gamma$  is the surface tension and  $R$ , the local radius of curvature, is positive in areas of convex curvature and negative where the droplet's surface curvature is concave.

Therefore the vapor film's pressure gradient is such that vapor flows away from the concave point A in figure 3 toward the two convex points B. Linke and company argue that while vapor flowing toward B<sub>1</sub> easily escapes laterally along the saw-tooth trench, the vapor flowing toward B<sub>2</sub> remains in closer contact with the droplet, exerting a shear force that impels it toward the right.

The group's analysis makes the arguments quantitative by measuring surface curvatures and vapor film heights on the digitized video images. The best model fits describe the velocity evolution well. Figure 2 shows that the fit improves with increasing temperature above the Leidenfrost point. As temperature is lowered toward  $T_L$ , the data become increasingly ragged. The suspicion is that at the lower temperatures—albeit still above the quoted  $T_L$  for clean, ungrooved brass—there is some surface wetting, and therefore boiling and surface-tension imbalance, near the saw-tooth tips. The model reproduces well the dependence of the ratchet's accelerating force on droplet size for droplets large enough to cover two or three ratchet periods.

## Applications and undergrads

The Oregon group found that the effect can also propel a droplet forced to run a kind of gauntlet between ratcheted side rails a few millimeters apart—even when the floor is smooth and unratch-



**Figure 3.** Straddling a ratchet saw tooth, a drop of liquid cushioned by a vapor layer will have concave and convex patches of undersurface. Because the vapor's pressure is highest under the most concave surface point and lowest under the most convex, vapor will flow from A to B<sub>1</sub> and B<sub>2</sub>. The saw-tooth profile breaks the left-right symmetry. Vapor flowing left can escape laterally along the trench formed by the tooth. But vapor flowing right creates a strong shear force that pulls the droplet along. That effect is thought to be the principal mechanism propelling liquid droplets along such ratchets above the Leidenfrost temperature.<sup>2</sup>

eted. Such narrowly channeled propulsion could be important for applications.

The possibility of microfluidic applications like lab-on-a-chip technology (see PHYSICS TODAY, March 2006, page 19) raises the question of whether the Leidenfrost ratchet effects can be scaled down to smaller dimensions. But the most promising practical application, thinks Linke, avoids that issue. Millimeter droplets would be a plausible size for a system designed to cool square-centimeter microprocessor chips. "The next generation of computers will dissipate up to 100 watts of heat per chip," says Linke, "and that's a very serious problem."

To remove heat from microproces-

sor chips with a circulating coolant fluid would ordinarily require a pumping mechanism that adds heat of its own. "What makes the Leidenfrost ratchet idea so appealing," says Linke, "is that the heat generated by the chips might be all you need to circulate the coolant." The envisioned scheme is a closed channel in which evaporated coolant would eventually recondense. And the device would need neither moving parts nor thermostatic control.

"Of course we have to investigate whether such a scheme could provide adequate cooling power," says Linke. To that end, the Leidenfrost project recently applied for its first research grant. Until now the undertaking has had an unusually avocational character. "Most of my coauthors were undergraduates," says Linke. "They did the real work." When he was at the University of New South Wales in Australia before coming to Oregon in 2001, his summer student Matthew Francis

scratched a ratchet surface onto plexiglass with scissors and sandpaper. The makeshift prototype was sufficiently promising that Linke, when he got to Oregon, recruited more undergraduates, together with physicist Richard Taylor and Vinod Narayanan, a professor of mechanical engineering, to study the effect in earnest.

**Bertram Schwarzschild**

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3. Videos of self-propelled Leidenfrost droplets are available at <http://www.uoregon.edu/~linke/dropletmovies/>.

## physics update

Supplementary material related to these items can be found at [www.physicstoday.org](http://www.physicstoday.org).

**Sharpened focusing of hard x rays.** Because of their high energy and weak interaction with matter, hard x rays ( $\lambda < 0.1$  nm) are difficult to focus, whether by reflection, refraction, or diffraction. Recently, scientists at Argonne National Laboratory fabricated what they call a multilayer Laue lens (MLL)—alternating layers of metal and silicon deposited with nanometer precision in progressively thicker layers, then cut in cross

section like a slice of layer cake. When illuminated nearly edge-on, with x rays skimming the interfaces, the layers form a sequence of Fresnel diffraction zones. The MLL succeeds both because of the precise zone tolerances and because the depth of the zones can be made microns long by merely cutting a larger section of the multilayer wafer. In tests, an incomplete MLL was tilted less than 1 mrad away from 0.064-nm (20-keV) x rays coming out of Argonne's Advanced Photon Source, and focused the x rays to a line only 30 nm wide, better than previously possible. The researchers say that an ideal MLL should be able to focus hard x rays to a spot of 1 nm or less, which would make it useful for microscopes and micro-