OPTICS

Thermal exploration in engine design

A negative-temperature heat engine is achieved with photons

By **Lincoln D. Carr**[1] and **Valentina Parigi**[2]

The air we breathe is filled with molecules that can be represented mathematically in a Boltzmann probability curve as a descending exponential distribution of low- to high-energy states. In this context, the average ambient temperature (20°C), for example, is more likely to reflect a state of many more molecules with low energy than high energy and a temperature with a positive sign. Such an exponential distribution has a lower bound of zero energy but no upper bound. However, systems can be designed to have an upper bound in energy such that higher energies are more likely than lower energies. In this case, although we "feel" the same ambient temperature of 20°C, it bears a negative sign to account for exponential growth in energy toward this bound. On page 1019 of this issue, Marques Muniz *et al.* (*1*) demonstrate just such a system, with interacting photons instead of molecules.

The findings of Marques Muniz *et al.* contribute to an expanding landscape of thermal possibilities for device design. This space now includes negative temperatures observed in contexts as varied as magnetic spins (*2*, *3*), cold atoms in optical lattices (*4*), and vortices in two-dimensional hydrodynamics (*5*). It also includes the many "temperatures" needed to fit thermal distributions that are studied in quantum simulators and computers (*6*) and the conversion of information to energy. The latter is leading to a new understanding of classical and quantum nanothermodynamics as well as the second law of thermodynamics (*7*).

Far from being mathematical peculiarities, these thermal explorations have real consequences in the design of thermodynamic devices. Foremost among these is the heat engine, an essential concept and building block of all combustion engines in, for example, cars, boats, and planes. This is because temperature is connected to energy and entropy, two of the key concepts in engine design. In an energetically unbounded system, the entropy increases with energy—more energy means more possible states of the system. Thus, as a system gets hotter, it becomes more disordered. But in an energetically bounded system, it can be shown mathematically that entropy decreases with increases in energy, so that as a system gets hotter, it can actually order. This is a negative temperature, from an entropy perspective. Heat engines, such as the idealized and maximally efficient Carnot engine, involve stages of expansion and compression of a substance at a fixed temperature (isothermal) and fixed entropy (isentropic) while exchanging heat energy with the environment.

The study of Marques Muniz *et al.* is exciting because of its new experimental context for achieving negative temperature—interacting photons in a nonlinear optical system. The system does not require extreme conditions such as ultracold atoms in optical lattices (*4*). But even more exciting is the demonstration of building blocks for a heat engine that operates in negative temperature (achieving lower entropy as it gets hotter), which may surpass the maximal efficiency of an ideal Carnot engine (*8*). This points to a more-efficient engine, which means less energy to produce the same work.

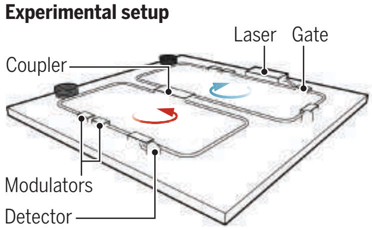
Photons are noninteracting when in a vacuum and therefore cannot thermalize (pass energy between them to relax to an exponential). Such an optical system is called linear. However, when photons are in a medium, those of high-enough intensities can interact with each. Such an optical system is nonlinear (*9*–*13*). Marques Muniz *et al.* created a nonlinear optical system with fiberoptic loops that achieved negative temperature with a photon gas in a time-synthetic lattice. Photons travel repeatedly through the same two fiberoptic loops and collide and split at a coupler (see the figure), which creates a two-dimensional lattice of light modes that are "synthetic" (not a lattice in physical space). In this system, a mode of light is defined by the specific time and specific place in the loops of a pulse. The two key elements in creating the time-synthetic lattice are that one loop is shorter than the other and that the two loops are brought together with the variable coupler.

How exactly did Marques Muniz *et al.* create a lattice from just two fiberoptic loops? Laser pulses containing photons go around the two rings, intersect, and split at the coupler. They do this over and over, which leads to a lattice of light modes. The y axis of the lattice represents the average length (L) that a photon travels along the two loops such that $y = mL$ (where m is the number of times a pulse has traveled in the two loops). The x axis is related to the time it takes for a photon to travel around the two rings. What is important is the timing difference in photon arrival at the coupler. Here, $x = n\Delta t$, where Δt is the timing difference and n is the number of time differences that have accumulated.

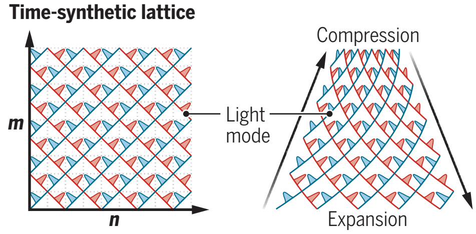
The time difference and the total number of time differences are controlled by the variable coupler and the phase and amplitude modulators that are positioned in the

A thermodynamic test bed

A pair of fiberoptic loops that is packed with light pulses allows photons to interact with each other and jump between pulses. The resulting modes of light can be described in a lattice picture. The device can be used to explore an engine design in which the system achieves more order as it gets hotter.



Two coupled fiberoptic loops (red and blue) that have slightly different lengths create a timing difference. A laser injects light pulses that then split into the two loops through a coupler. Light amplitude and phase can be modulated along the loops.



Laser pulses from the short (red) and long (blue) loops are observed as a function of the number of round trips (m, spatial variable) and the number of accumulated time differences (n, time variable). Varying the coupling between loops slowly creates isoentropic compression or expansion by bringing the lattice mode sites closer or further apart.

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fiberoptic paths. Also, the nonlinearity in the fiberoptic loops means that photons can interact. Thus, photons can jump from one pulse to another through nonlinear interactions and redistribute into different modes. The photons can thereby thermalize just like a gas. The result is a highly controllable thermodynamic testbed for designing a negative-temperature heat engine that uses a photon gas as a working substance. For instance, the total size of the lattice can be increased or decreased with the variable coupler, thus increasing or decreasing the number of modes. The internal energy of the system can also be changed while keeping the number of modes constant.

The time-synthetic lattice is described by lattice band theory, which is analogous to the energy bands of a crystal lattice. The upper energy bound within each band is necessary to realize negative temperatures. In this system, negative temperatures are created just by adding more energy. For example, by increasing the intensity of the laser light that is injected to the loop system of Marques Muniz *et al.*, the energy of the system can be increased, which leads to a negative temperature. The variable coupler allows the abrupt doubling of the number of occupied modes to realize a sudden expansion of a photon gas. By contrast, if the lattice time difference between modes is resized slowly, then isentropic compression and expansion can be implemented, which are the building blocks of a heat engine. Throughout these processes, the negative temperature is stable, thus confuting the notion that negative temperatures are not practically useful (*14*).

As negative temperatures become realizable in accessible experimental contexts such as nonlinear optics, a rapid exploration of their impact can be expected, from the design of nanoscale superefficient engines (*8*) to quantum transport devices (*14*) to the generalization of the many-temperature distributions found in quantum simulators and computing (*6*). ■

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ANIMAL BEHAVIOR

Bees learn to dance

Experience yields precision in the waggle dance of honey bees

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Many animals can guide or call other members of their group to a rich foraging site (*1–3*). By contrast, honey bees have a distinctive form of communication that allows them to send nestmates to the location of a food source by using symbols. The coordinates are encoded by intricate movements (the "dance") on the vertical wax comb in the hive, using gravity and time as references. The motions are followed by recruits in the darkness of the hive, who subsequently decode the extracted flight vector information and follow the dancer's instructions once outside (*4*). Like many of the elaborate behaviors of social insects, this communication system was thought to be innate. However, on page 1015 of this issue, Dong *et al.* (*5*) reveal that honey bees only deliver precise spatial information in their dances if they previously had the opportunity to attend dances by experienced role models—the communication system must in part be learnt socially.

After the discovery of a rich food source, honey bee (genus *Apis*) foragers can recruit nestmates by performing a figure-of-eight–shaped dance (consisting of a central "waggle run" followed by alternating left and right semicircles) on the vertical wax combs inside the hive, with followers touching the dancer's abdomen with their antennae. The duration of the straight waggle run informs the others about the distance to the bounty. Direction of the target relative to the Sun is encoded in the angle of the waggle run, so that a waggle run straight up means "fly toward the Sun's azimuth" and a waggle run at an angle 20° to the right of the vertical means "fly 20° to the right of the Sun's azimuth" (*4*). The full dance circuit is repeated many times over to allow dance followers to average out variation of the display. There are indications that dance behavior is at least in part genetically encoded: All species of honey bees exhibit a form of this communication, and no other bee species do. Moreover, subtle variations of the dance code within the genus are species specific, and the information contents are largely preprogrammed in that they are limited to information about location and quality and cannot easily incorporate new "words" (new symbols with new meanings) in the same way that human language can (*6*).

However, if the waggle dance was fully innate, young bees would display the dance correctly even if they had never witnessed the behavior. Dong *et al.* created bee colonies composed exclusively of newly emerged bees; without any guidance from tutors, these bees began displaying waggle dances at the typical age of 1 to 2 weeks after emergence from the pupae (*7*). But the location indications from such inexperienced bees were highly variable from one dance circuit to the next and consistently indicated distances longer than the bees had actually traveled. Recruits would have struggled to find the indicated location. As the immature bees gained experience over the coming 20 days, the variation of their location codes gradually reached normal levels. However, distance indications remained abnormally high for life, indicating that after a critical time window, adjustments through social learning are no longer possible (*8*). Bees from control colonies, which had exposure to dances of seasoned foragers before initiating their own, displayed none of these shortcomings.

Why does any element of the dance language have to be learnt if the end point of the learning is always a dance of the same pattern and precision? There are two possible scenarios—one is similar to human locomotion, whereby everyone has to learn to walk, but the outcome is predictable. The alternative scenario is that there might be flexibility in the outcome of learning (the dance patterns displayed) depending on the environmental conditions encountered by bees. This indicates the exciting possibility that the link between symbol and meaning could be learnt, as in human communication.

Could it be that what is socially learnt is not just the precise choreography, but the translation of the information provided by other bees' dances into the actual coordinates of food sources subsequently encountered by the dance attendees? In

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