Under these controlled conditions, the authors tracked individual mosquitoes in flight.

Insects that had been pre-exposed to solvent alone had no trouble flying upwind along the CO_2 plume to its source. However, mosquitoes pre-exposed to the ultra-prolonged blend seemed to get lost along the way — they were slow to get started, meandered, and took more time to reach the source, if they reached it at all. Because the insects had been pre-exposed to the blend before entering the wind tunnel and did not encounter it during the test, the authors could rule out the possibility that the misdirected mosquitoes had been distracted in flight by detecting blend components through other types of receptor neurons. This result directly links the insensitivity of the cpA neuron to the inability of the mosquito to track CO_2.

For a more realistic test, Turner and colleagues conducted a study in Kenya. There, within a large enclosure, they assembled two draughty huts typical of the region. Both huts contained mosquito traps releasing alluring plumes of CO_2, but one also contained a vaporizer dispensing the authors' ultra-prolonged blend. The mosquitoes were released into the enclosure overnight. By morning, compared with the relatively unprotected hut, only half as many mosquitoes had been trapped in the hut containing the ultra-prolonged blend.

These results[1] bode well for the hunt to find a means of avoiding mosquitoes. Inhibitory odorants might help to mask the presence of humans; CO_2 mimetics may provide advantages for luring mosquitoes into traps; and ultra-prolonged activation agents dispersed through the air might shield whole groups of people. But because mosquitoes are also attracted to other human body odours in sweat, breath and skin[7], it remains to be seen how effective these compounds will be for protecting people.

Moreover, as the authors note, the chemicals they have tested so far, including 2,3-butanedione, have not been shown to be safe for humans. But the principles that these compounds reveal are definitely not safe for mosquitoes. ■

Mark Stopfer *is at the National Institute of Child Health and Human Development, National Institutes of Health, Bethesda, Maryland 20892, USA.*
e-mail: stopferm@mail.nih.gov

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QUANTUM INFORMATION

Entanglement as elbow grease

Quantum correlations have long been recognized as an informational resource for quantum communication and computation. It now seems that they can also do physical work. SEE LETTER P.61

PATRICK HAYDEN

It is a fact, confirmed through mundane and repetitive experience, that it's much easier to make a mess than to clean one up. Our personal battles to keep our desks tidy and our houses clean remind us every day that nature is inclined to disorder. That preference is so pronounced that it has a name: the second law of thermodynamics. Entropy measures disorder, and the second law states that entropy cannot decrease. On page 61 of this issue, del Rio *et al.*[1] show that, even though the second law itself is inviolable, clever quantum engineering can sometimes make it possible to sneak around the law's well-known consequence that erasing information requires an investment of physical work.

The importance of erasure becomes clear from asking a simple question. Is computation, with its constant and complicated reordering of the states of the computer, more akin to cleaning a house or messing it up? Back in 1961, Rolf Landauer made a profound, if tautological, observation[2]: the only necessarily irreversible steps in a computation are those that erase information. Erasing a bit of information (which can have a value of either '1' or '0') by setting it to '0' is the logical equivalent of cleaning a messy house, which means that it should take some effort. Indeed, resetting a bit from an unknown state to '0' reduces the computer's entropy by exactly one bit, so the second law of thermodynamics requires that bit of entropy to get shuttled somewhere else.

Ultimately, the entropy ends up in the environment, in the form of an amount $k_B T \ln 2$ of heat, where k_B is Boltzmann's constant and T is the temperature. Anyone who has noticed their computer's temperature rise precipitously as it works on a demanding problem, such as decoding a streaming video, has witnessed at first hand the dissipation of heat associated with irreversible computation. (Of course, today's technology is thermodynamically inefficient, dissipating orders of magnitude more heat than required by Landauer's principle.)

In fact, there is no fundamental need for computation to erase bits at all. A computer could just use fresh bits at every stage of its computation, never erasing anything. But in reality, such a computer would rapidly run out of memory. In the 1980s, however, Charles Bennett found[3] a cleverer approach based not on storing used bits but on reversibly uncomputing them. Unlike erasing bits, this eliminates the need to dissipate heat. Bennett's reversible computation has a central role in quantum computation because fundamental logic gates in quantum computation are naturally reversible.

So, if inventive physicists and engineers manage to build a quantum computer someday, it will be based on reversible logic, never erasing any of its quantum bits (qubits). Or will it? In their study, del Rio *et al.*[1] present a counter-intuitive revision of Landauer's principle that is applicable to quantum states. In some circumstances, erasing a qubit need not heat up the environment at all, but instead can cool it down. Equivalently, instead of having to invest work to erase the qubit, the process of erasing the qubit can actually generate work, like a tiny quantum-logical wind turbine.

As is often the case with surprising features of quantum information, entanglement — a kind of superstrong quantum-mechanical correlation — is the resource making the effect possible. One of the fundamental lessons of quantum information theory is that entanglement is more than just a conceptual puzzle; it is a resource that can be exploited, for example to send qubits over long distances via teleportation[4] or to establish secrets for use in cryptography[5]. The study by del Rio *et al.* demonstrates convincingly that entanglement is not just an informational resource, but a physical one. Entanglement can literally do work.

To see how this comes about, consider trying to design a machine that will erase a bit, resetting it to '0'. If the bit is already '0', the machine doesn't need to do anything. If the bit is '1', the machine needs to flip it. Neither of these actions is irreversible, so it would seem possible to erase the bit without leaking any heat to the environment, violating Landauer's principle. The trick is that, to decide whether to leave the bit alone or to flip it, the machine has first to read the bit, inadvertently creating a copy of it somewhere else. Such a machine isn't erasing the bit so much as just moving it around in memory. The way to avoid such sneaky sleights of hand is to keep track of not just the bit being erased but the whole computer memory, requiring that the memory be left just as it was found once the erasure process has finished.

Using the symbol S for the system being erased and M for the memory, the amount of work required to erase the system is $H(S|M)k_BT\ln 2$. The function $H(S|M)$, known as the conditional entropy of S given M, measures how much residual uncertainty about S there is, given the contents of M. If S is a pair of random bits, for example, M might store whether those two bits are the same or different. In that case, although S itself contains two bits of entropy, $H(S|M) = 1$ because, given M, knowledge of one bit is enough to figure out the other, leaving only one bit of residual uncertainty about S.

As usual, though, quantum mechanics makes things a bit stranger. If the system and memory are entangled with each other, then $H(S|M)$ can be negative: a machine with access to the memory M can be "more than certain" about the system S (ref. 6; for a non-technical discussion, see ref. 7). Mathematically, the reason this happens is that the conditional entropy can be expressed as $H(S|M) = H(S,M) - H(M)$, the amount of entropy in the pair (S,M) that cannot be attributed to M. Highly entangled states can have high-entropy parts and a low-entropy whole — that is, large $H(M)$ but a small $H(S,M)$, leading to a negative $H(S|M)$. Intuitively, this is a reflection of the fact that there is more to an entangled quantum state than just the assemblage of its disordered parts. In their study, del Rio and colleagues prove that the work cost of erasure in quantum mechanics remains $H(S|M)k_BT\ln 2$, even when $H(S|M)$ is negative, in which case erasing doesn't cost work, it generates it.

The authors[1] explain how to build a machine that would extract the work, but other than in the simplest cases, the machine would have to execute some sophisticated quantum computations. No ordinary heat engine, its building blocks would be highly efficient quantum error-correcting codes first invented to solve communications problems. Del Rio *et al.* creatively adapt those codes to establish a new and fundamental link between the information content of quantum correlations and more familiar physical concepts such as heat and work. ■

Patrick Hayden *is in the School of Computer Science, McGill University, Montreal, Quebec H3A 2A7, Canada.*
e-mail: patrick@cs.mcgill.ca

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IMMUNOLOGY

In command of commensals

Humans must maintain a balanced composition for the trillions of commensal microbes that inhabit their gut, but how they do this is largely unclear. It now emerges that one factor is a molecular pathway in gut epithelial cells.

MENNO VAN LOOKEREN CAMPAGNE & VISHVA M. DIXIT

Homeostatic equilibrium between microbes in the gut lumen of the human host is crucial. Gut microbiota can aid digestion and suppress pathogenic bacteria. So when the spectrum of these resident microbes is altered, it can allow pathogenic species to elicit an inflammatory cascade in the gut mucosa, and inflammatory bowel disease can develop[1]. Reporting in *Cell*, Elinav *et al.*[2] show that the protein NLRP6 in gut epithelial cells guards against harmful imbalances in the microbiota: in mice lacking this protein, microbial communities are altered, triggering both spontaneous and induced inflammation of the large intestine (colitis).

NLRP6 is related to three other proteins — NLRP1, NLRP3 and NLRC4 — that respond to specific stimuli by forming large multiprotein complexes called inflammasomes. As part of the inflammasome, the enzyme caspase 1 triggers activation of the pro-inflammatory (inflammation-inducing) cytokine proteins IL-1β and IL-18, which are then secreted[3]. An adapter protein known as ASC bridges the interaction between the NLR proteins and caspase 1 (Fig. 1a).

In a series of elegant experiments, Elinav and colleagues[2] show that genetic ablation of NLRP6 in mice profoundly reduces inflammasome activation in the intestine, alters the microbiota there and increases the animals' susceptibility to colitis. This severe intestinal inflammation results in significant weight loss. Moreover, the colitis-causing (colitogenic) microbiota could be transferred across

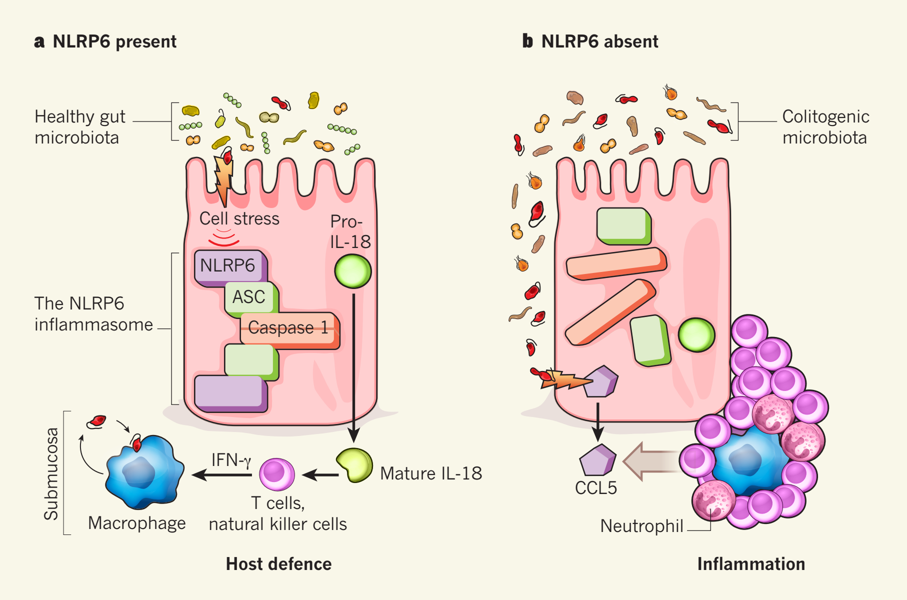

Figure 1 | The NLRP6 inflammasome — a guardian of intestinal homeostasis. a, Normally, intestinal epithelial cells respond to pathogenic bacteria that reside among commensal microbiota by mobilizing the NLRP6 inflammasome. Specifically, dimerization, and so activation, of caspase 1 results in the proteolytic conversion of pro-IL-18 into mature IL-18. The latter is secreted, stimulating production of IFN-γ in subsets of activated T cells or in natural killer cells in the submucosa. IFN-γ in turn promotes the bactericidal activity of macrophages. **b,** Elinav *et al.*[2] show that NLRP6-deficient epithelial cells fail to mount an appropriate response to pathogenic bacteria. Consequently, the normal microbial composition in the intestinal lumen is altered to that of a colitogenic community. These microbes stimulate epithelial cells to secrete the chemokine CCL5, which attracts immune cells such as neutrophils to trigger a chronic inflammatory response that can manifest as inflammatory bowel disease.