Physics Today

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Citation: Physics Today 67(8), 60 (2014); doi: 10.1063/PT.3.2490
View online: http://dx.doi.org/10.1063/PT.3.2490
View Table of Contents: http://scitation.aip.org/content/aip/magazine/physicstoday/67/8?ver=pdfcov
Published by the AIP Publishing

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A simple model illustrates the operating principles of an information engine, a mechanical device that mimics the behavior of Maxwell's demon by converting heat into information plus work.

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A liter of ordinary air weighs less than half a US penny, but it contains enough thermal energy to toss a 7-kg bowling ball more than 3 m off the ground. A gadget able to harvest that abundant energy by converting the erratic movement of colliding molecules into directed motion could be very useful indeed. Of course, the second law of thermodynamics forbids any device whose sole effect is the extraction of energy from a single thermal reservoir and its conversion into work. But that prohibition has not prevented nearly 150 years of imaginative thinking about the possibilities and impossibilities of rectifying thermal noise, changing it from random to directional.

That happy tradition traces back to James Clerk Maxwell, who in 1867 conjured up a creature—now known as Maxwell's demon—situated near a tiny opening in a partition that separates the two chambers of a gas-filled box. By blocking the passage of unusually fast molecules from the right chamber to the left and of slow molecules moving in the opposite direction, the creature brings about a systematic accumulation of fast particles in the right chamber and slow ones in the left. In Maxwell's words, "the hot system has got hotter and the cold colder and yet no work has been done, only the intelligence of a very observant and neat-fingered being has been employed." The temperature difference set up by the demon can drive a heat engine, converting thermal energy into useful work in defiance of the second law.

Information entropy

Beginning with the work of Rolf Landauer in the early 1960s and continuing with that of Oliver Penrose and Charles Bennett, there emerged an understanding of Maxwell's demon in which the concept of information appears as a key ingredient. The basic idea is sketched in figure 1. Any entity that rectifies thermal noise must make measurements and thereby gather information. In Maxwell's thought experiment, the information resides in the knowledge gained by an intelligent demon. But when a real contraption makes measurements, the information it gathers must be stored in a physical memory register, represented in figure 1 as a tape that moves past the device. The tape contains a sequence of equally spaced bits (two-state systems), all arriving in the same "0" state; thus the incoming tape encodes no information. As the bits go past the apparatus, interactions with the device may change the bit states and thereby write information to the outgoing bit stream.

In converting a sequence of 0s into a mixture of 0s and 1s, the device increases the entropy of the memory register and offsets the decrease of entropy associated with the conversion of heat into work. Thus a blank memory register is a thermodynamic resource: Its capacity to soak up information can be traded for useful energy.

We found it instructive and enjoyable to cook up an explicit, mechanical model of an information engine such as depicted in figure 1. We approached the task as an exercise in *gedanken* engineering, with the goal being a gadget that systematically withdraws energy from a single thermal reservoir and delivers that energy to lift a mass against gravity while writing information to a memory register.

The details of the devil

The demon we came up with is shown in figure 2. It is a ring that rotates frictionlessly around a central axis without wobbling. A small blade attached to the ring points inward toward the central axis. As depicted in the figure inset, we will let θ_D denote the angular orientation of the demon blade. The bits take the form of paddles organized along a vertical rod aligned with the central axis of the demon. Each paddle is free to rotate about the rod. The rod moves frictionlessly downward and carries the bits downward, one by one, through the plane of the demon. The rod and bits are balanced by a counterweight, so no external force is required to maintain that vertical motion. The entire contraption is immersed in an ideal gas of particles at a fixed temperature. Each collision of a gas particle with the demon blade or a bit paddle leads to an energy exchange between the rotational motion of the blade or paddle and the translational motion of the particle.

Information is encoded in the angular orientation of each paddle, θ_B. As shown in the figure inset, when $0 \le \theta_B < \pi$, the bit is in the 0 state; when $\pi \le \theta_B < 2\pi$, the bit is 1. Two fixed

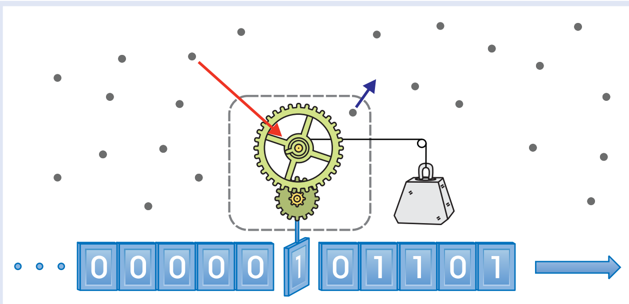

Figure 1. An autonomous device able to convert thermal energy into work to raise a mass against gravity must also write information to a physical memory register, here represented by a moving tape of 0s and 1s.

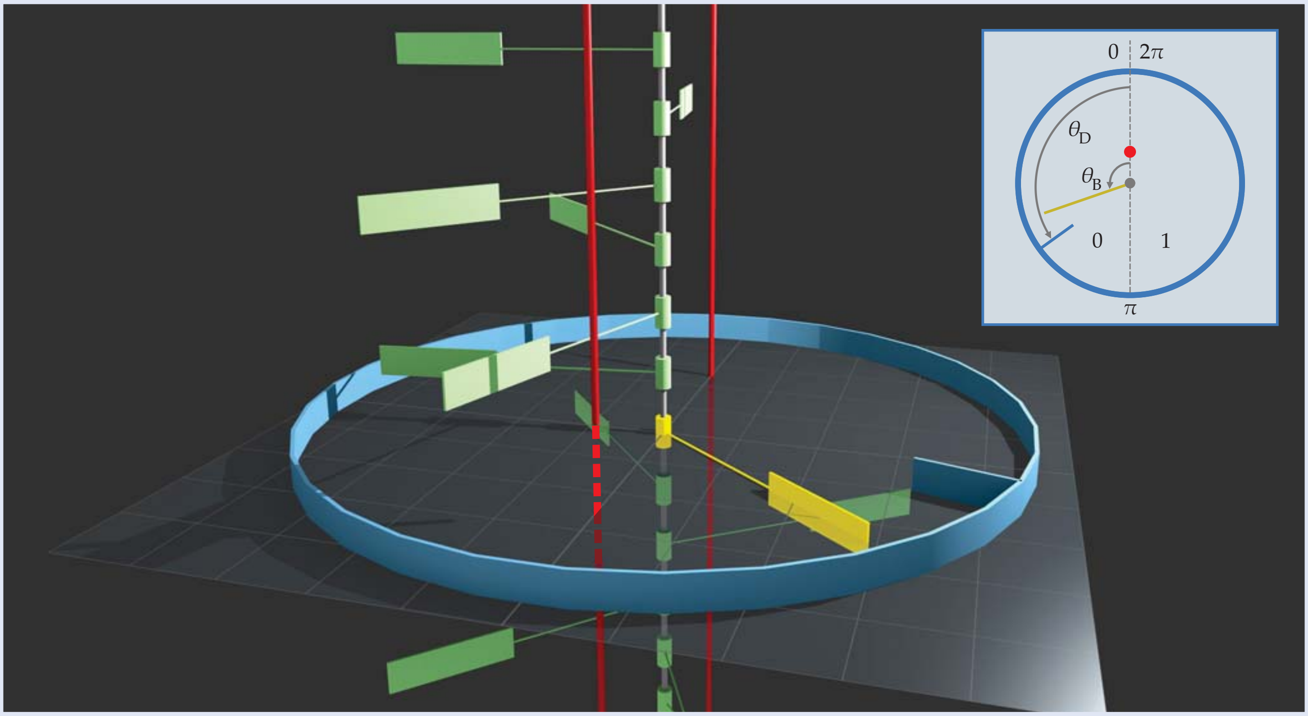

Figure 2. Our mechanical demon is a blue ring with an attached blade. The green and yellow paddles realize a stream of bits that move past the demon, and the yellow one is currently able to interact with the demon. Two red, vertical rods block the motion of the bit paddles, but one of the rods has a gap (dashed line) centered at the height of the demon. The device is immersed in an ideal gas of particles. The inset defines the angular orientations of the demon blade (θ_D) and the yellow bit paddle (θ_B) with respect to the gapless blocking rod (red dot). If, at the time when blade and paddle can first interact, $\theta_B < \theta_D$, as illustrated here, the demon can execute a full counterclockwise rotation but is prevented from making a full clockwise rotation.

rods, parallel to the central axis and located at $\theta = 0$ and $\theta = \pi$, block the motion of the bits so as to ensure that the state of each incoming and outgoing bit remains constant. However, the blocking rod at $\theta = \pi$ has a gap that is vertically centered with the demon. When a particular bit reaches that gap, it can change its state by rotating through the gap. Moreover, the bit paddle can collide elastically with the demon blade; indeed, the gap is constructed to ensure that the interval of time during which a bit can rotate through the gap coincides with the interval during which it can undergo collisions with the blade. By construction, all incoming bits arrive in the 0 state. To see our device in action, check out the animation at http://youtu.be/00TyIShzR6o.

In the long run, the demon rotates counterclockwise (CCW). To see why, consider what happens in the time interval during which a particular bit is aligned with the gap. If the bit arrives at the gap with $\theta_B < \theta_D$, as in the figure 2 inset, then the demon cannot complete a full clockwise (CW) rotation; its motion is eventually blocked by the combination of the bit and the blocking rod at $\theta = 0$. But the demon can rotate more than 360° in the CCW direction. On the other hand, if the bit arrives with $\theta_B > \theta_D$, it is the CCW rotation that is blocked. By construction, however, each bit arrives with a θ_B between 0 and π, the 0 state, whereas at bit arrival time, the demon blade can be found anywhere between 0 and 2π. Thus the first case ($\theta_B < \theta_D$) occurs more frequently than the second, a bias that ultimately results in the CCW rotation of the demon.

The rotating demon can be used to lift a tiny mass. The potential energy gained by the mass comes from the surrounding ideal gas, whose entropy is thereby decreased. Moreover, a final bit state of 0 is statistically correlated with CW demon rotation, and a final state of 1 is correlated with CCW motion. For example, for the $\theta_B < \theta_D$ case, a final bit value of 1 indicates that CCW rotation occurred as the bit paddle passed through the blocking-rod gap. A final value of 0, however, could accompany either CW or CCW motion. Still, the outgoing bits provide a historical record—albeit an imperfect one—of the rotary motion of the demon and so our gadget meets the goal we had set for it.

The engine in reverse

We have validated the above arguments with analytical calculations and numerical simulations, but the main point of our exercise was to create a simple, transparent model to illustrate how an information engine might operate. By converting an incoming stream of 0s into an outgoing mess of 0s and 1s, our device generates enough entropy in the bits to enable the transformation of thermal energy into mechanical work.

Interestingly, our gadget can operate in reverse. If the incoming bits arrive in an equal mixture of randomly distributed 0s and 1s, then the mass falls instead of rising, and the demon rotates clockwise; our device erases information, harnessing the energy of the falling mass to produce an outgoing bit stream that is less random than the incoming one. That mode of operation illustrates Landauer's principle, which states that the erasure of information inevitably carries a thermodynamic cost—in our example, the loss of gravitational potential energy.

Additional resources

▶ R. P. Feynman, R. B. Leighton, M. Sands, *The Feynman Lectures on Physics*, vol. 1, Addison-Wesley, Reading, MA (1963), chap. 46.

▶ H. S. Leff, A. F. Rex, eds., *Maxwell's Demon 2: Entropy, Classical and Quantum Information, Computing*, Institute of Physics, Philadelphia (2003).