Demons, Engines and Information

Can a clever 'demon' outsmart the second law of thermodynamics?

Heat cannot pass from a cooler to a hotter body without some other process occurring. — second law of thermodynamics

By IVARS PETERSON

No one expects a refrigerator to keep its contents cold without the expenditure of energy. The second law of thermodynamics sees to that. Because heat doesn't spontaneously flow from a colder to a hotter body, it takes energy to extract heat from a refrigerator to make it cold.

But is that always true? In 1871, the Scottish physicist James Clerk Maxwell considered the idea that a microscopic being, small enough to see and handle individual molecules, might be exempt from the second law.

Maxwell envisioned such a creature standing at a small hole in a partition dividing a gas-filled box into two compartments. By controlling which molecules pass through the hole, the creature could effortlessly direct slow-moving molecules into one section and fast-moving molecules into the other. Thus, without apparently expending any energy, it could make one compartment hot and the other cold, thereby violating the second law of thermodynamics.

This hypothetical creature became known as Maxwell's demon. Such a mischievous being — if it existed — would allow refrigerators to operate without an energy source. Indeed, machines of all kinds could function simply by using a swarm of demons to create temperature differences, which one could then exploit to do useful work — a recipe for perpetual motion.

Since Maxwell's day, theorists have spent countless hours trying to save the second law, pondering why his demon and those imagined by others could not actually do their jobs in the ways described. The theorists' defenses for the second law hinge on a variety of subtle, energy-dissipating effects, including the mechanical characteristics of demon-operated trapdoors suitable for selectively letting certain molecules through a hole in a partition while excluding others.

Some theorists are now taking a fresh look at the whole problem from the demon's point of view, taking into account what information the demon must gather and use to direct heat into useful work. They ask, "What does the demon know, and when does it know it?"

"I think all of us believe that the second law of thermodynamics is valid," says William G. Unruh of the University of British Columbia in Vancouver. However, keeping track of the information a demon needs, including the way it stores and erases that information, offers a very different way of looking at thermodynamics, he says. It's worth testing an information-based theory's logic to see how it handles situations involving the second law of thermodynamics.

This information-based approach, adds Wojciech H. Zurek of the Los Alamos (N.M.) National Laboratory, "casts new light on the limitations of Maxwell's demon."

One of the simplest examples of a demon-operated machine, known as Szilard's engine, exists only in the minds of theorists. It consists of a box containing a single molecule and equipped with a movable partition that can drop down to divide the box into two halves. Frictionless pistons cap the box's left and right ends. When the partition drops, the demon determines in which half of the box the molecule is trapped, moves the piston on the empty side of the box up to the partition, lifts the partition and lets the molecule shove the piston back to its original position. That allows the molecule to do work, in apparent violation of the second law of thermodynamics.

One explanation for why this demon actually fails, put forward by Charles H. Bennett of the IBM Thomas J. Watson Research Center in Yorktown Heights, N.Y., is that an additional step is necessary to complete the engine's cycle. The demon's memory initially stores one bit of information: whether the molecule is in the left or the right half. The demon must eventually clear its mind, erasing that information so that the system is ready for the next cycle. But erasing a bit of information uses sufficient energy to cancel out any energy gained elsewhere.

In the April 30 Physical Review Letters, Carlton M. Caves of the University of Southern California in Los Angeles tries to circumvent that problem. His system consists of a number of Szilard engines coupled together. To make it work, Caves requires the demon to gather information economically so that, in the end, less information will need erasing.

In effect, he instructs the demon to examine the set of boxes and store the information only if the molecules — one to a box — happen to be in an arrangement that can be described concisely. For example, if all the molecules happen to be on the right-hand side of their boxes, then the demon could record the entire configuration in, say, a single bit. It could then extract work from all the molecules, yet it would finally have to erase only one bit.

However, because such easy-to-record configurations would happen rarely, the demon could extract work only by waiting for just the right kinds of fluctuations in the distribution of molecules. "Not surprisingly, the demon wins occasionally, and the second law is 'violated' in particular cases," Caves states in his paper. Thus, it would appear, the second law has a modest loophole.

On the other hand, if you regard the second law of thermodynamics as valid, this disturbing result seems to call into question some aspects of the information-theory approach to thermodynamics. But theorists have found a way to save the day.

Shortly before his paper appeared in print, Caves described his calculations at a conference at the Santa Fe (N.M.) Institute. Concerned by the results, several theorists present at his talk took up the question and eventually identified an additional, previously overlooked erasure cost that effectively wipes out any gains the demon might make by using only rare, easy-to-describe molecular arrangements.

"It shows that the demon can't win at all — can't achieve even the very small limits that I had derived in my paper," Caves says. "So the second law again wins absolutely, contrary to what I said in the paper."

The trouble is that the demon must carry additional bits in its memory to show whether or not it decided to use a particular configuration. Otherwise, it could get caught in a loop: looking at a set of boxes, rejecting that configuration, storing no information, then not knowing whether it had checked that configuration, looking at it again and so on.

To avoid getting caught in such a loop, the demon ends up with a memory filled with a string of essentially random digits distinguishing between the useful arrangements and the rejected arrangements. There's no compact way of expressing this information, Zurek says. The extra cost of erasing these digits exactly cancels any energy gain elsewhere in the system.

"In other words, rare fluctuations don't do you any good," Zurek says. Caves, Unruh and Zurek have prepared a brief paper for publication in PHYSICAL REVIEW LETTERS that clarifies the situation.

Are there any other potential loopholes? Zurek, for one, thinks that there's at least one more worth exploring.

"A lot of our original thinking had to do with a situation where the Maxwell's demon is completely deterministic," Zurek says. "In other words, it works like a computer should. One instruction is completed before it goes on to the next instruction."

What isn't so clear is what would happen if the demon could "wander" a little. What if the demon knew its instructions but wasn't quite sure of the order in which to carry them out? The demon would then proceed from one step to another, going forward or backward, in a somewhat random fashion. In the long run, that might allow the demon to extract some work from the system.

"It sounds fanciful, but I think there's a loophole there to be closed," Zurek says. "I have no doubt what the outcome of the argument is going to be, but I'm still missing a nice way of stating the reason for the demon's failure—from the demon's point of view."

As this latest episode demonstrates, tangling with Maxwell's demon and the second law of thermodynamics is not for the faint of heart. Theorists entering the fray must be unusually adept at their craft — and extremely careful. "It's such a confusing thing, and so many people get snagged," Bennett says.

The episode also shows the potential for applying a branch of theoretical computer science, known as algorithmic information content analysis, to questions in thermodynamics. For example, such an information-based approach provides an alternative way of looking at the degree of disorder, or entropy, in a system.

Scientists usually express a system's degree of disorder in terms of statistical measures of, say, the distribution of molecules in the system. But it's also possible to consider the changes in entropy associated with acquiring or erasing the information someone needs and uses to make a measurement or to describe the state of a physical system.

"Only algorithmic information content allows one to consistently develop a formalism from the point of view of the entity that requires information," Zurek says. "I suspect this will have implications not only for second-law thermodynamics but also for things like quantum-theory measurements."

"People made mistakes in the past by thinking that information was almost magically separate from physics — something separate from the medium in which it was stored," Bennett says. In reality, "the value that a bit [of information] could have is just like the volume of space a molecule could be in."

In other words, the distinction between information and physical objects is somewhat artificial. "Thinking of information as outside of physics — as being merely in the human mind — is silly," says Bennett. "Information *is* in physics." □

Continued from p.377

Ghiradella says she has found both types of structures in different scales of the same butterfly. The distances between individual layers and "bubbles" usually fall in the 300-to-700-nanometer range — the same range of electromagnetic wavelengths that humans see as colors. For some effects, such as reflecting shorter-wavelength ultraviolet light, the distances are even smaller.

Davis has examined multilayered scales in which chitinous layers alternate with "air blankets" at specific distances that determine which wavelengths, or colors, of incoming light will get reflected. These thin, chitin-air layers act "like stacked oil slicks," Ghiradella adds. In some cases, they function as prisms, refracting different colors at different angles so that the wings assume different hues depending on the observer's viewing point.

Besides serving as pixels for wing designs, scales may act as solar collectors to heat wing muscles, Davis suggests. "These insects have to raise their body temperature a certain amount before they can get their engines started in the morning," he says. That may explain why butterflies often appear to bask in the sun before flitting into the air.

The scales also serve a sacrificial role that enables butterflies and moths to get out of dangerous tangles. "When the insect hits a spiderweb, because its scales are loose, it can break free by shedding those scales," Eisner notes.

Whether admired for their architectural intricacies or for their many varieties of chromatic splendor, lepidopteran wings evoke fascination and delight. As Eisner puts it, "They give us a sense of the beautiful."

For Sandved, the sense of beauty deepens with each new discovery of a human symbol in these wild but gentle beings. He laments that the rapid disappearance of many butterfly habitats will bar researchers from retracing the evolutionary paths that have led to such a spectacular diversity of designs.

For Ghiradella, the microstructural elegance of the scales demonstrates that lepidopteran beauty is more than a mere cover. And for anybody strolling in a mountain meadow, hiking through an Appalachian forest or sweltering in a tropical jungle, the fluttering creatures serve as public announcements that art abounds in nature. □