MAXWELL'S DEMON

breaking the laws of thermodynamics

By Angelo Mao

In late 1867, Scottish physicist James Clerk Maxwell proposed a thought experiment that produced an invalidation of the second law of thermodynamics. Maxwell's experiment involved a "Demon," whose actions are summarized in an excerpt from Thomas Pynchon's famous 1966 novel, The Crying of Lot 49 (2):

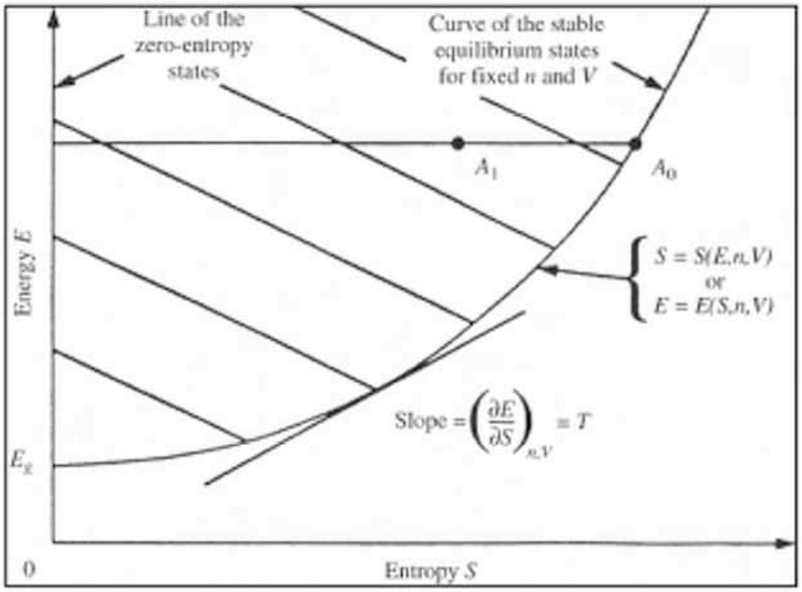
The [Maxwell's] Demon could sit in a box among air molecules that were moving at all different random speeds, and sort out the fast molecules from the slow ones. Fast molecules have more energy than slow ones. Concentrate enough of them in one place and you have a region of high temperature. You can then use the difference in temperature … to drive a heat engine. Since the Demon only sat and sorted, you wouldn't have put any real work into the system. So you would be violating the Second Law of Thermodynamics, getting something for nothing, causing perpetual motion.

Maxwell's proposition precipitated a long process of exorcism, as scientists from fields as varying as quantum mechanics to computer science attempted to provide a sound argument that could keep the Second Law of Thermodynamics intact. Along the way, the nature of Maxwell's Demon and entropy itself has received rigorous examination, leading to shifts in our understanding of fundamental physical laws that Maxwell himself may not have predicted.

Statistical Entropy and the Intelligent Demon

The first major turn in literature concerning Maxwell's Demon occurred sixty years after its conception. By the time Leo Szilard wrote his seminal 1929 paper, Einstein and Smoluchowski had confirmed both the existence of atoms and the fact that, on a microscopic scale, these particles made random movements. The implications for the second law of thermodynamics arose

The Second Law of Thermodynamics: "In an isolated system, a process can occur only if it increases disorder, or entropy.[1]"



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A graphical representation of the entropy versus energy of a system with fixed amount of constituents and volume.

in the form of two questions: should entropy be expected to increase for each movement of each particle, or only for a statistical sum of all movements of all particles in a container, as hypothesized by the work of earlier scientists including Maxwell himself? Secondly, how should scientists take into account the potential entropic expenditure of the Demon's intelligence? That is to say, how would the act of gathering and processing the velocities of different particles affect the analysis of Maxwell's Demon?

Szilard decided to view entropy in statistical, rather than absolute, terms. His attempts to protect the second law of thermodynamics therefore assumed that an individual random movement might decrease entropy, but that the statistical average of all movements would lead to an increase in entropy. The reason for this, Szilard claimed, was that the intelligence needed to select for random movements that decreased entropy actually produced an entropic cost. That is to say, the act of gathering information incurred an entropic cost (3).

The Cost of Knowledge

By the latter half of the twentieth century, exorcists of Maxwell's Demon had shifted focus to two previously unsuspected nexuses of potential entropic expenditure: the acquisition of knowledge and the removal of existing knowledge. The first grew out of Szilard's paper and became known, fittingly, as Szilard's Principle. This principle put into words the intuition that the Demon's "radar," used to detect the velocities of moving particles, incurred an entropic cost in and of itself. Therefore, for every reduction in entropy the Demon effected, there was an equal entropic gain from the act of ascertaining the properties of the molecule. The proof for Szilard's Principle was rooted into the equivalence between information and entropy. However, this congruency ran afoul of the Third Law of Thermodynamics, which stated that entropy reached a minimal value at absolute zero. Because information was unaffected by temperature, the two were not equitable. Another postulate had to be proposed to carry on the exorcism (4).

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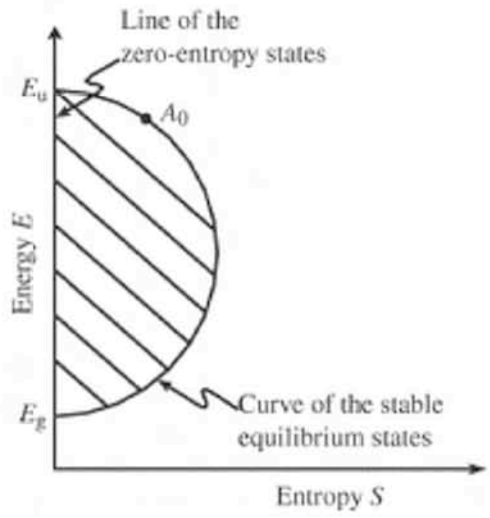
This new rule came in the form of Landauer's Principle, which shifted the focus of entropic gain to the erasure, not gathering, of knowledge. Because knowledge had to be contained as physical units on some kind of information hardware, a change in knowledge, as would occur when a Demon analyzed a new particle, would result in increased entropy. The weakness in Landauer's Principle, however, lay in its premises, which drew heavily on technicalities concerning information hardware. Rapid developments in information technology and the un-empirical nature of the proof for Landauer's Principle are two serious challenges facing scientists who wish to exorcize Maxwell's Demon using information entropy as a basis (5).

Nonstatistical Entropy and Homogenous Equilibrium

The loose ends of Szilard's and Landauer's Principles have led some scientists to go back to the drawing board. One assumption that had underlain almost all existing strategies of exorcism was a statistical perspective of Entropy. Maxwell himself had this view in mind; the Demon's purpose was to demonstrate that '[t]he 2nd law of thermodynamics has the same degree of truth as the statement that if you throw a tumblerful of water into the sea, you cannot get the same tumblerful back.' Recent work in theoretical physics has led to a revaluation of the statistical nature of entropy, instead treating it as a nonstatistical property of a system.

Gyftopoulos's exorcism is based on his redefinitions of the laws of thermodynamics in terms of the states of a physical system. From his laws, he reconstructs entropy as a property S depending on E, energy, n amounts of r different constituents, and β different credit: 6



Another graph of entropy versus energy with fixed external parameters, as well as an upper limit on energy in the system.

external properties:

$$S = S(E, n_1, n_2 ... n_r, \beta_1, \beta_2 ... \beta_s)$$

The state of a system can be represented graphically by a point existing on multidimensional axes, each of which represents a parameter such as n or β. If all external and constituent parameters are held as given, then the state of a system can be projected onto a two-dimensional energy versus entropy graph.

> *"The second approach Fryftopoulos embraces stems from the counterintuitive argument that, at thermodynamic equilibrium, each molecule in a system at stable equilibrium is at a standstill."*

Based on Gyftopoulos's definitions of thermodynamic laws, the shaded regions represents all possible energy and entropy states of a system, with the boundary representing stable equilibrium. Thus, a Demon would be unable to move the state of a system towards increased energy and decreased entropy without requiring compensation for leaving equilibrium (6).

The second approach Gyftopoulos embraces stems from the counterintuitive argument that, at thermodynamic equilibrium, each molecule in a system at stable equilibrium is at a standstill. He concedes that this claim seems contradicted by chemical spectroscopic data, which gives measurements of molecular velocity. However, Gyftopoulos also asserts that our understanding of measurements may not be complete, and that the information we gain regarding molecular velocity may not accurately characterize systems in their prior states. For instance, scientists can detect a photon even though there was no photon in the prior state. As such, a system at stable equilibrium may not have a heterogeneous population for the Demon to sort (7).

Conclusion

When Maxwell envisioned his anti-entropic demon, he may not have imagined how much it would trouble later generations. Much work over the years has gone into the creation of thought-machines that purportedly function as a Maxwell's Demon, but more important has been the trail of shifting scientific paradigms traced out by subsequent exorcism attempts. The path started with statistical entropy and wound through various incarnations of information entropy. More recently, it has seen a revaluation of the nature of entropy and the laws of thermodynamics themselves. While the latest exorcism, centered on the state function and homogeneous nature of thermodynamics, claims to be the Demon's death knell, it remains to be seen whether this banishment will hold. Maxwell's Demon may yet return to trouble physicists both now and in the future. ■

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Appendix

Boltzmann, whose eponymous constant connected the velocity of moving particles to temperature, postulated that entropy could be defined as:

$$S = k_b \ln \Omega$$

for a system at thermodynamic equilibrium, where kb is Boltzmann's constant, and Ω is the number of microstates consistent with the overall state of the system . Much of statistical entropy is derived from this equation.

Building on Boltzmann's equation for entropy a difference between two states, Ω1 and Ω2, can be denoted as such:

$$I = k_b \ln \frac{\Omega_1}{\Omega_2}$$

This is I, the information entropy.

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