The law beats Maxwell's demon

SIR—John Maddox' review of the Maxwell's demon case (*Nature* **345**, 109; 1990) provokes the comment that the cited approaches to the problem are misguided.

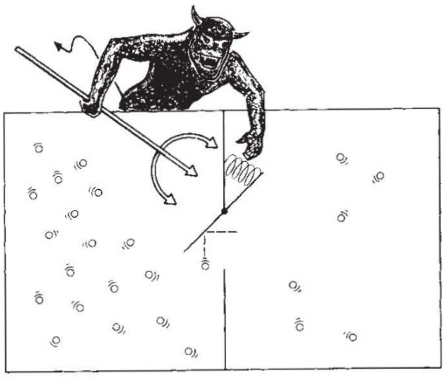
First, it is not clear what the rules of the game are for the demon. If the demon has to obey the laws of physics, then what are the arguments about? If it is immune from the physical law, then why the physical implication of the demon's computational effect (energy consumption)? And what physically interesting conclusions could possibly be drawn by considering an agent operating outside physical law?

Second, if we settle for a mechanical demon — one that obeys the canon of physics (dynamics) — it will contain some moving parts; physically, the demon is a system with some physical degrees of freedom. But classical statistical mechanics postulates that, for a system in thermal equilibrium, the energy is equally partitioned among all the degrees of freedom. Because the demon is coupled to the system, it would get its share of the equipartitioned energy. The question is, then, would this fluctuating infusion of energy nullify the demon's anti-second law effort? It could be retorted that the objective of the demon is to prevent a thermodynamic equilibrium in the first place, but then to what does the temperature T in the expression $kT \log_e 2$, the energy of computing, refer?

As an illustration, consider a simple example of a box partitioned into two equal halves by a wall, the halves containing an equal number of molecules. Suppose there is a small, almost massless, door in the wall which opens only from one side when struck by a molecule from that side. Suppose further there is a small spring attached to the door which automatically closes the door after a molecule has passed through it. That is our mechanical demon.

With this arrangement, should we not expect more molecules be assembled in one half rather than in the other, making a pressure gradient that could be used for extracting work in contradiction to the second law of thermodynamics? It could be argued that the kinetic energy acquired by the door through equipartition keeps it in motion, allowing molecules to pass in both directions with equal probability. Furthermore, to stop the door from recoiling after being slammed, a dissipative stopping mechanism would be required, whence any gain in negative entropy through a pressure gradient would be offset by an increase of entropy through the dissipation process of the slamming door.

This raises a third point. No assessment of the energy required for processing bits of information can be based on Maxwell's demon-type arguments. An expression like $kT \log_e 2$ makes reference to the statistical concept of temperature. Clearly, one cannot substantiate such a formula through examples with only one or two molecules, which is more like the situation of zero temperature, at which entropy and pressure are assumed to be zero anyway. Instead, to compute the energy needed for processing information, one has to make a



physical model of the computer (and the environment) and apply basic physics (dynamics).

My last point is about dissipation. If the mechanical system is only "almost frictionless", there is still dissipation, which in the long run builds up entropy. And if it is assumed to be completely frictionless, it will become severely agitated through equipartition. Also, the Poincaré recurrence theorem would apply; that states that the system recurs arbitrarily close to its initial state after a time long enough. Thus the 'second law of thermodynamics' would have to be conditioned by the estimate of the probability of finding the system in the state of maximal entropy.

Finally, I would put the demon's problem this way: as a cognitive being (like Laplace's demon), the demon has all the freedoms and power of heaven and hell, but as soon as the demon tries to temper with earthly matters, it is under the jurisdiction of physical law.

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SIR—Maddox (*Nature* **345**, 109; 1990) reverts to Maxwell's demon and subsequent discussions by Szillard and others concerning its practical use to circumvent the second law of thermodynamics and elude energy constraints. Can the demon in theory defend or resolve the Boltzmann paradox of purporting to deduce a macro time-asymmetric one-sided increase in entropy from time-reversible microscopic differential equations?

The answer is no. If a demon could operate as described, the resulting microscopic differential equations are non-hamiltonian. This is not so much because of some special violation of energy conservation, but rather because the observable particles going through apertures or being reflected from trapdoors obey new differential equations that are definite, but definitely not time-symmetric. There is no paradox to be resolved when time-asymmetric microscopic equations entail macroscopic measurements that are time-asymmetric.

To confirm the point, consider a frictionless trough containing two perfectly elastic balls and being bounded by perfectly elastic walls at each side. Before Maxwell's interfering, the balls proceed from their specified initial positions and velocities according to Newton's simplest law of non-acceleration — until a ball hits a wall or another ball. By definition of 'perfectly elastic' entities, approximatable in real-life experiments, a ball reverses its direction instantly without losing speed just when hitting a wall; two balls that collide, if of the same mass, instantaneously exchange their velocities. When averaged over all future time, each half of the trough has the same mean number of balls. (Their temperatures average out equal, so to speak.) Of course, the history of the specified system going backwards in time obeys precisely the same kind of newtonian equations. Whatever statements I can make about 'mean temperatures' or about 'entropy' going forwards in time can be matched by a valid similar deduction going backwards in time.

But take Maxwell's demon. It changes linear differential equations such as $\ddot{y}_i(t) \equiv 0$ and impulsive reversals of velocities at walls and collisions into nonlinear differential equations that are complicated only to write down. Let $(-1, 1/2, +1)$ be respectively the values of a $y_i(t)$ when at the left wall, at the middle of the trough where the demon slides in Maxwell's trapdoor, at the right wall. Before the demon, when the y_i are away from the walls and are separated, they everywhere satisfy $\ddot{y}_i = f(\dot{y}_1, \dot{y}_2; y_2, y_2)$ where $f(\ ,\ ) \equiv 0$ for $y_1 \neq y_2$ and $|y_1| \neq 1$, $|y_2| \neq 1$. Now, when y_1 is near the trapdoor and away from y_2, the demon will want to shepherd y_1 into, let us say, the left-hand corral. Effectively, between collisions the demon replaces Newton's laws by its own new rules

$$\dot{y}_i(t+) = D[\dot{y}_i(t-), y_i(t)]$$

where

$$D[\dot{x}, x] = \dot{x} \quad \text{for } x \neq 1/2$$

$$D[\dot{x}, 1/2] = \dot{x} \quad \text{for } \dot{x} < 0$$

$$= \dot{x} \quad \text{for } \dot{x} > 0$$

To convince oneself of the time-asymmetry of the demonized system, ask where the system had been a short time before observing both balls in the left-half corral with one moving just to the left of the trough's midpoint. One cannot say whether the last ball will have just been trapped, and therefore that it was recently