Demons, Engines and the Second Law

Since 1871 physicists have been trying to resolve the conundrum of Maxwell's demon: a creature that seems to violate the second law of thermodynamics. An answer comes from the theory of computing

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One manifestation of the second law of thermodynamics is that such devices as refrigerators, which create inequalities of temperature, require energy in order to operate. Conversely, an existing inequality of temperature can be exploited to do useful work-for example by a steam engine, which exploits the temperature difference between its hot boiler and its cold condenser. Yet in 1871 the Scottish physicist James Clerk Maxwell suggested, in his *Theory of Heat,* that a creature small enough to see and handle individual molecules might be exempt from this law. It might be able to create and sustain differences in temperature without doing any work:

> "...if we conceive a being whose faculties are so sharpened that he can follow every molecule in its course, such a being, whose attributes are still as essentially finite as our own, would be able to do what is at present impossible to us. For we have seen that the molecules in a vessel full of air at uniform temperature are moving with velocities by no means uniform.... Now let us suppose that such a vessel is divided into two portions, A and B, by a division in which there is a small hole, and that a being, who can see the individual molecules, opens and closes this hole, so as to allow only the swifter molecules to pass from A to B, and only the slower ones to pass from B to A. He will thus, without expenditure of work, raise the temperature Of B and lower that Of A, in contradiction to the second law of thermodynamics."

The "being" soon came to be called Maxwell's demon, because of its far reaching subversive effects on the natural order of things. Chief among these effects would be to abolish the need for energy sources such as oil, uranium and sunlight. Machines of all kinds could be operated without batteries, fuel tanks or power cords. For example, the demon would enable one to run a steam engine continuously without fuel, by keeping the engine's boiler perpetually hot and its condenser perpetually cold.

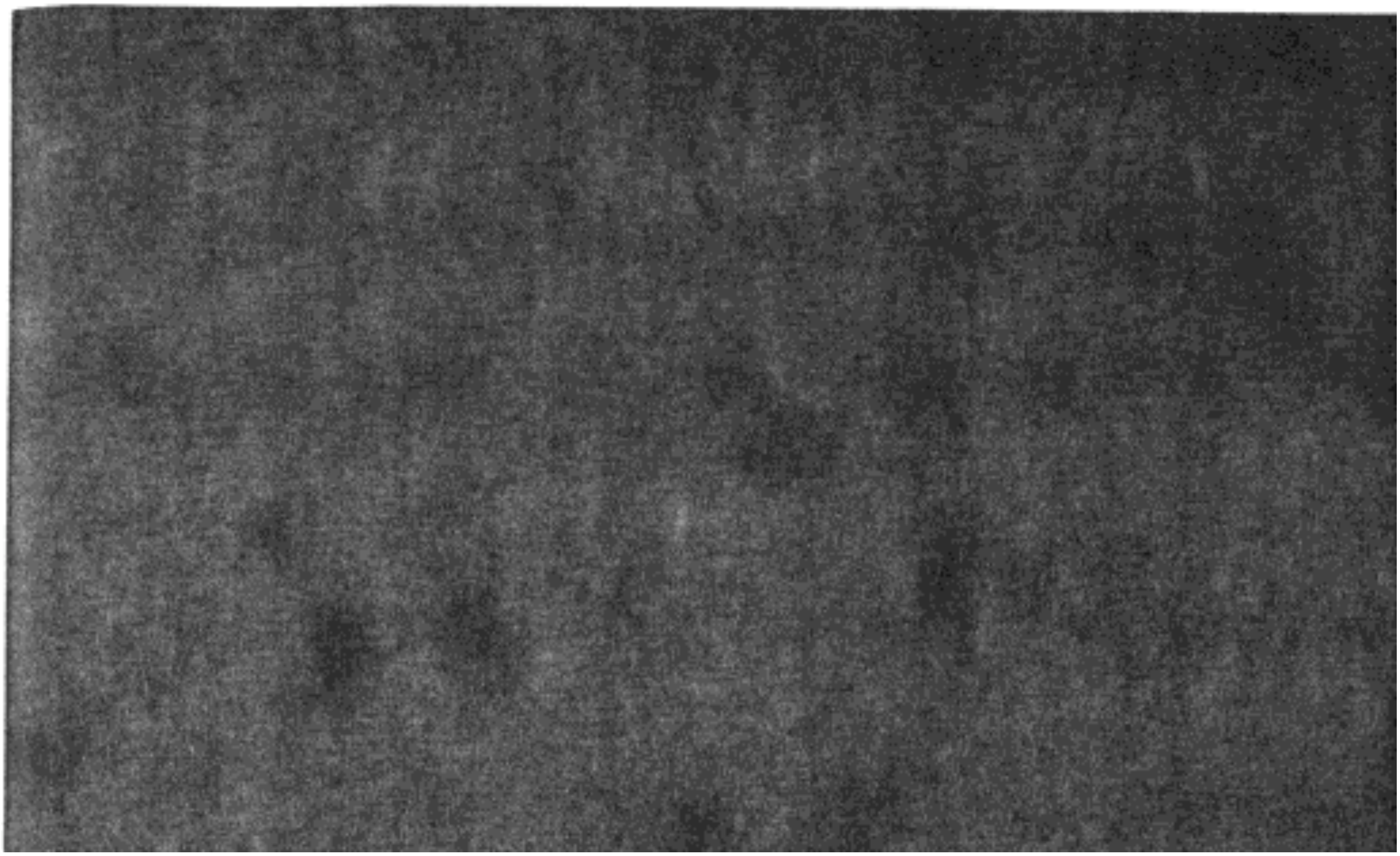
To protect the second law, physicists have proposed various reasons the demon cannot function as Maxwell described. Surprisingly, nearly all these proposals have been flawed. Often flaws arose because workers had been misled by advances in other fields of physics; many of them thought (incorrectly, as it turns out) that various limitations imposed by quantum theory invalidated Maxwell's demon.

The correct answer-the real reason Maxwell's demon cannot violate the second law-has been uncovered only recently. It is the unexpected result of a very different line of research: research on the energy requirements of computers.

Since Maxwell's day numerous versions of the demon have been proposed. One of the simplest creates a pressure difference (rather than a temperature difference) by allowing all molecules, fast or slow, to pass from B to A but preventing them from passing from A to B. Eventually most of the molecules will be concentrated in A and a partial vacuum will be created in B. This demon is if anything more plausible than Maxwell's original demon, since it would not need to be able to see or think. It is not immediately evident why such a demon - a one-way valve for molecules-could not be realized as some simple inanimate device, for instance a miniature spring-loaded trapdoor.

Like Maxwell's original demon, the "pressure demon" could be a source of limitless power for machines. For example, pneumatic drills of the kind used to cut holes in streets generally run on compressed air from a tank kept full by a gasoline-powered compressor. A one-way valve for air molecules could substitute for the compressor, effortlessly collecting air from the surroundings into the high pressure tank.

One might think such an arrangement would violate the law of conservation of energy (otherwise known as the first law of thermodynamics), but it would not. The energy for cutting concrete could be taken from heat in the air collected by the one-way valve; the air's temperature would drop as it passed through the machinery. There is nothing in the first law to prevent an engine from supplying all its energy needs from the ambient heat of its environment. or even from the waste heat of its own friction and exhaust. It is the second law that prohibits such engines.



Uniform glow in a hot furnace (top) demonstrates one consequence of the second law of thermodynamics: it is impossible to distinguish objects in a vessel at uniform temperature without an external light source hotter than the vessel's ambient temperature. In a vessel at uniform temperature objects glow in such a way that exactly the same intensity and color of light come from the surface of every object (even objects that have different reflectances and colors). The reason is that if any object appeared darker than its surroundings, it would absorb energy at the expense of its neighbors. As a result it would become hotter and its neighbors would become cooler. According to the second law, however, objects that are initially at the same temperature cannot spontaneously come to have different temperatures. (In this photograph some contrast is visible because the temperature inside the furnace is not exactly uniform.) By an external light source, intrinsic differences in reflectance are visible (bottom).

To analyze the demon's actions, closely, then, one must understand some of the subtleties of the second law. The second law was originally expressed as a restriction on the possible transformations of heat and work, but it is now seen as being fundamentally a statement about the increase of disorder in the universe. According to the second law, the entropy, or disorder, of the universe as a whole cannot be made to decrease. This means that only two kind,, Of events are possible: events during which the entropy of the universe increases and events during which it remains constant. The former are known as irreversible processes because to undo them would violate the second law; the latter are called reversible processes. One can decrease the entropy of a given system by doing work on it, but in doing the work one would increase the entropy of another system (or that of the first system's environment) by an equal or greater amount.

A classic irreversible process, and one that helps in defining the concept of entropy a little more precisely, is called free expansion. Suppose a chamber filled with gas is separated by a partition from a vacuum chamber of the same size. If a small hole is made in the partition, gas will escape (that is, it will expand freely) into the formerly empty chamber until both chambers are filled equally.

The reason the molecules spread out to fill both chambers is mathematical rather than physical, if such a distinction can be made. The numbers of molecules on the two sides of the partition tend to equalize not because the molecules repel one another and move as far apart as possible, but rather because their many collisions with the walls of the container and with one another tend to distribute them randomly throughout the available space, until about half of them are on one side of the partition and about half are on the other side.

Since the spreading of the molecules is due to chance rather than to repulsion, there is a chance that all the molecules might return simultaneously to the chamber from which they came. If there are n molecules, however, the probability of all of them returning to their original chamber is the same as the probability of tossing n coins and having them all come up "heads": 1/2n. Thus for any sizable number of molecules (and there are about 300,000,000,000,000,000,000,000 molecules in a gram of hydrogen) the free expansion is an effectively irreversible process: a process whose spontaneous undoing, although possible, is so unlikely that one can say with confidence it will never be observed.

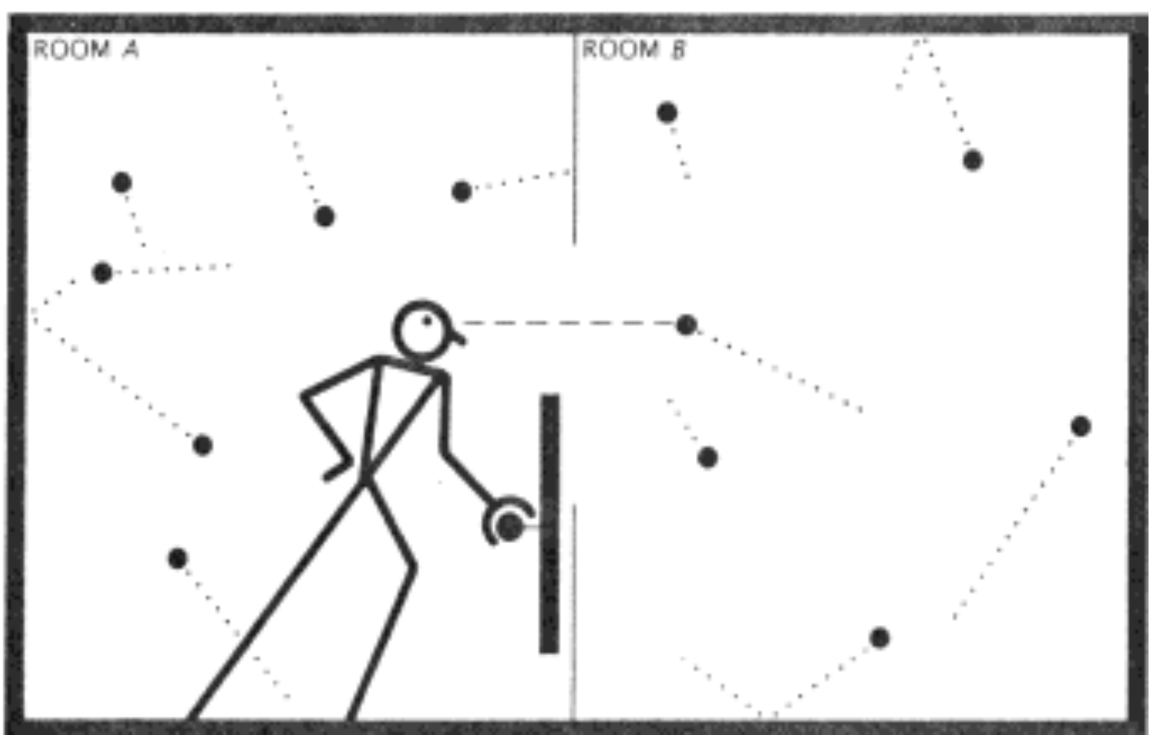
The disordered state-the state in which the gas has spread into both chambers rather than residing compactly in a single chamber is more probable than the ordered state. That is, there are more configurations of molecules in which the molecules occupy both chambers, just as, when 100 coins are tossed, there are more ways to achieve a total of 50 heads and 50 tails than there are to achieve 100 heads and no tails. In saying that the entropy of the universe tends to increase, the second law is simply noting that the universe tends to fall into more probable states as time passes.

Can this concept be quantified? In other words, can one say how much the disorder of the gas has increased after it has spread out to fill both chambers? Consider a single molecule in the gas. A molecule that can roam throughout both chambers has twice as many possible positions as a molecule confined to a single chamber: there are twice as many ways for a molecule to occupy the two-chamber apparatus. if there are two molecules in the two-chamber apparatus, each molecule has twice as many possible positions as it would have in a single chamber, and so the system as a whole has 2 x 2, or four, times as many possible configurations. If there are three molecules, the system has 2 x 2 x 2, or eight, times as many possible configurations.

In general, if there are *n* molecules in the gas, the gas can fill two chambers in 2^n times more ways than it can fill a single chamber. The gas in the two-chamber apparatus is said to have 2^n times as many "accessible states" as the gas in a single chamber. In the same way, the number of accessible states in most systems depends exponentially on the number of molecules.

The entropy of a system is therefore defined as the logarithm of the number of accessible states. In the example of the two-chamber gas apparatus, a 2^n-fold increase in the number of accessible states is an increase in entropy of n bits, or binary units. (The base of the logarithm-and hence the size of a unit of entropy -- is arbitrary; it is conventional to choose base 2 and binary units.) The logarithmic scale has the advantage of making the entropy of a sample of matter, like its energy or mass, roughly proportional to the number of molecules in the sample. One can draw an analogy to a computer memory: an n-bit memory, other things being equal, has size, weight and cost that are roughly proportional to n although the number of distinct states possible in the memory is 2^n.

The earliest statements of the second law did not mention randomness or disorder; they concerned heat, work and temperature. How can these concepts be related to our quantitative definition of entropy?



Maxwell's Demon, described in 1871 by James Clerk Maxwell, seems able to violate the second law of thermodynamics. The demon controls a sliding door that blocks a hole in a wall between rooms containing gas at equal temperatures and pressures. It observes molecules approaching the hole and opens and closes the door to allow fast-moving molecules to pass from room A to room B but not vice versa. Slow-moving molecules, conversely, are allowed to pass only from B to A- As the demon sorts, B heats up and A cools. According to the second law, a certain amount of work is required to create a temperature difference, but the work of sliding a door can be made negligibly small.

The molecules in any sample of matter are always in motion. The speed and direction of each molecule are random, but the average speed of the molecules is proportional to the square root of the sample's temperature (as measured from absolute zero). As the temperature of a sample is raised (and the average speed increases) the velocities of individual molecules come to be distributed over a greater range than they are when the average speed is low.

When the average speed is high, then, every molecule in the sample has a greater range of velocities available to it, just as a' molecule in a two-chamber gas apparatus has a greater range of positions available to it than a molecule in a single-chamber apparatus has. There are thus more accessible states at high temperatures than there are at low temperatures. The motion is more disordered at high temperatures, because it is harder to predict what the velocity of any molecule will be.

Disorder of molecular motion and disorder of molecular positions must both be counted in determining the entropy of a system. The entropy of a gas can be increased either by allowing the gas to occupy a greater volume or by increasing its temperature so that its molecular motion becomes more disorderly.

Any flow of heat therefore carries entropy with it. To be precise, it turns out that a heat flow carries an amount of entropy proportional to the quantity of heat flowing divided by the temperature at which the flow takes place. Hence a flow from a hot body to a cold body raises the entropv of the cold body more than it lowers the entropy of the hot one: the same amount of heat leaves the hot body as enters the cold body, but in figuring the entropy decrease of the hot body one divides by a high temperature, whereas in figuring the entropy increase of the cold body one divides by a low temperature. A heat How from a hot to a cold body thus raises the entropy of the universe.

Our more precise definition of entropy gives us a better understanding of why Maxwell's demon seems to violate the second law. By its sorting action the demon is causing heat to flow from room A to room B, even after room B has become warmer than room A. The demon is therefore lowering the entropy of room A by a greater amount than it is raising the entropy of room B. The demon therefore decreases the entropy of the universe as a whole -- a thermodynamic impossibility.

In his description of the demon Maxwell made it clear he believed in the validity of the second law. He suggested that perhaps human beings are unable to violate the second law (by doing what the demon can do) simply because they lack the demon's ability to see and handle individual molecules. This is not a completely satisfying exorcism of the demon, because it leaves open the question of whether a being able to see and handle individual molecules, if such a being did exist, could violate the second law.

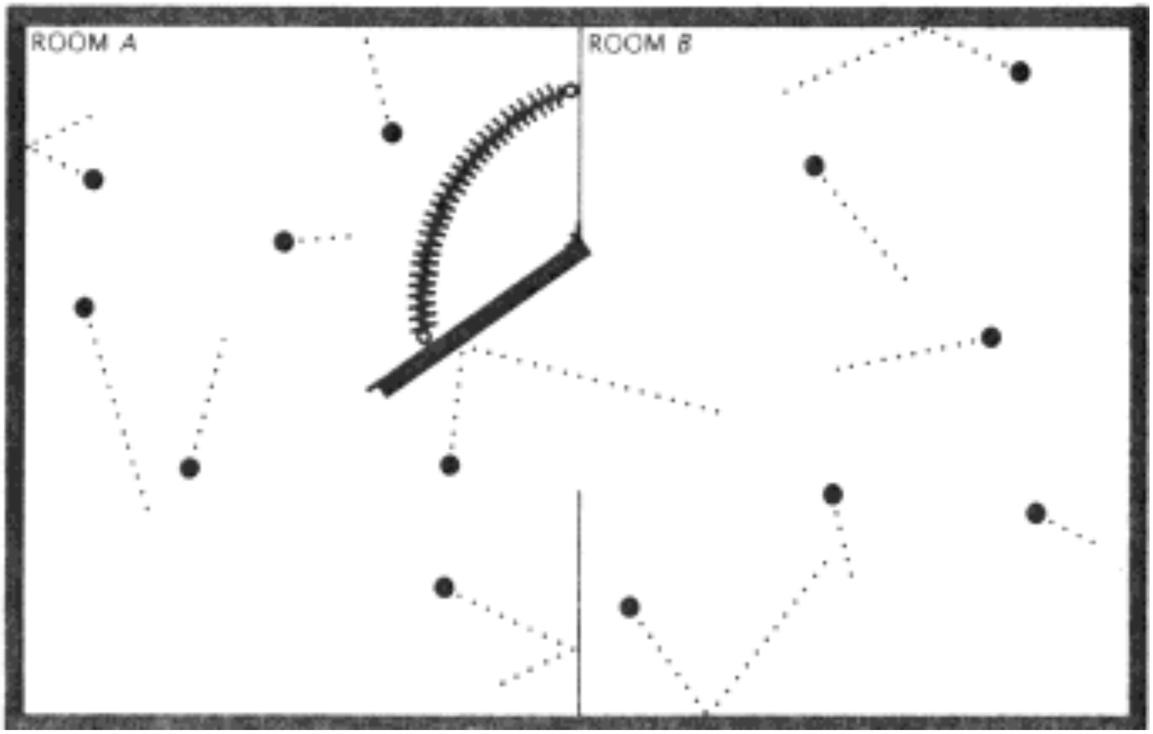
One way to uncover the reasons Maxwell's demon cannot work is to analyze and refute various simple, inanimate devices that might function as demons, such as the miniature spring-loaded trapdoor mentioned above, which acts as a one-way valve for molecules.

Imagine that the door opens to the left. If the demon works as it is supposed to, then every time a molecule from the room on the right strikes the door, the door swings open and the molecule passes into the room on the left. When a molecule from the left strikes the door, however, the door slams shut, trapping the molecule. Eventually all the molecules are trapped on the left, and the demon has compressed the gas (reducing its entropy) without doing any work.

How is the trapdoor demon flawed? First of all, the spring holding the door shut must be rather weak. The work of opening the door against the spring's force must be comparable to the average kinetic energy of the gas molecules. In 1912 Marian Smoluchowski pointed out that because the door is repeatedly being struck by molecules, it will eventually acquire its own kinetic energy of random motion (that is, heat energy). The door's energy of random motion will be about the same as that of the molecules striking it, and so the door will jiggle on its hinges and swing open and shut (remember that the door is very small), alternately bouncing against its jamb and swinging open against the force of the spring.

When the door is open, it obviously cannot function as a one-way valve, since molecules can pass freely in both directions. One might still hope that the door would act as an inefficient demon, trapping at least a small excess of gas on the left, but it cannot do even that. Any tendency the door has to act as a one-way valve, opening to let a molecule go from the right to the left, is exactly counteracted by its tendency to do the reverse: to slam shut against a molecule that has wandered in front of it, actively pushing the molecule from the room on the left to the one on the right (aided -by the force of the spring).

The two processes -- a 'molecule pushing its way past the door from right to left. and the door pushing a molecule from left to right-are mechanical reverses of each other: a motion picture of one, shown backward, would look like the other. In an environment at a constant temperature and pressure both processes would take place equally often, and the ability of the trapdoor to act as a one-way valve would be exactly zero. It cannot work as a demon.



Trapdoor "DEMON" is a form of Maxwell's demon designed to operate automatically and to create an inequality of pressure, not of temperature. A spring-loaded trapdoor blocks a hole between two rooms initially containing gas at equal temperatures and pressures. The door swings open in only one direction in order to admit molecules from room B into room A but not vice versa. Eventually, one might think molecules will accumulate in A at the expense of B, creating an inequality of pressure. Actually the inequality does not build up. The trapdoor, heated by collisions with molecules, jiggles open and closed randomly because of thermal energy. When it is open, it is not a one-way valve, and as it closes it may push a molecule from A into B. The latter process takes place as often as its inverse, in which a molecule from B pushes past the door into A.

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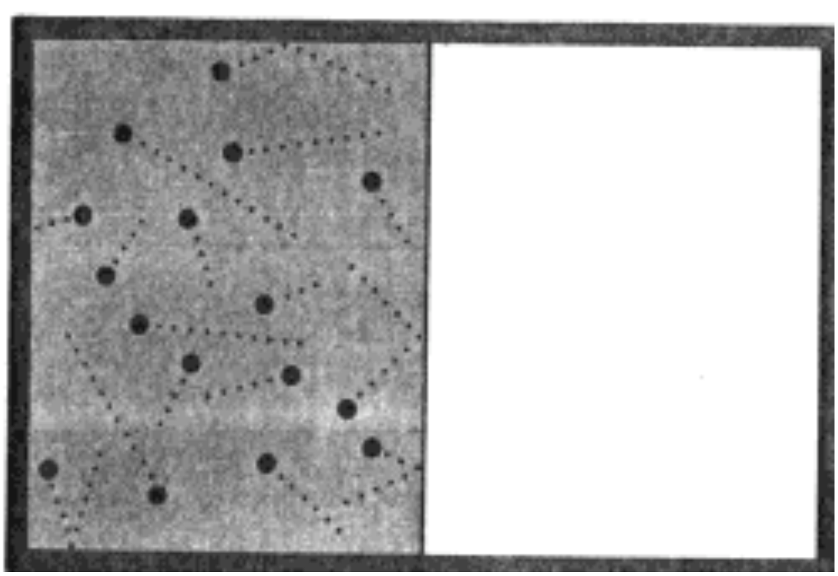

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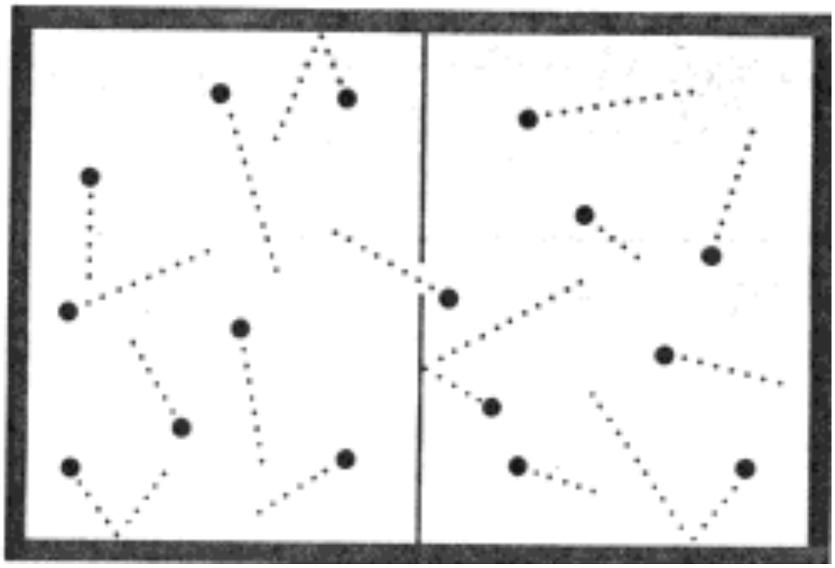


Free expansion of a gas is a thermodynamically irreversible process: one in which the entropy, or disorder, of the universe increases. A gas is initially confined in one chamber of a two-chamber apparatus (a). The barrier between the chambers is pierced, and molecules leak from one chamber into the other until approximately the same number of molecules are in both (b).

In environments where the pressure is not equal on both sides of the door, of course, such devices do function. Large-scale versions, built with macroscopic doors and springs, can be seen on ventilator fans designed to blow stale air out of restaurants without admitting gusts of outside air when the fan is off. Microscopic versions would function in much the same way, allowing molecules to pass if there were excess pressure on one side but shutting off the flow if there were excess pressure on the other. The devices would not violate the second law, because they could only allow pressures to equalize; they could never form regions of excess pressure.

Even though a simple mechanical demon cannot work, perhaps an intelligent one can. Indeed, some time after Maxwell had described the demon, many investigators came to believe intelligence was the critical property that enabled the demon to operate. For example, in a 1914 paper Smoluchowski wrote: "As far as we know today, there is no automatic permanently effective perpetual-motion machine, in spite of the molecular fluctuations, but such a device might, perhaps, function regularly if it were appropriately operated by intelligent beings."

The physicist Leo Szilard attempted a quantitative analysis of this question in a paper published in 1929, "On the Decrease of Entropy in a Thermodynamic System by the intervention of Intelligent Beings." A though the title seems to imply an intelligent demon could violate the second law, the body of the article is devoted to refuting this notion and to arguing that no being, intelligent or not, can do so. Szilard thought the observation, or measurement, the demon must make (for example, to se which side a molecule is coming from) cannot be done without also doing enough work to cause an in crease in entropy sufficient to pre vent a violation of the second law.

Szilard considered a demon that differed in several ways from Maxwell's; his demon has since come to be called Szilard's engine. (The engine I shall describe here differs slightly from Szilard's original one. The engine's main component is a cylinder in which there is a single molecule in random thermal motion. Each end of the cylinder is blocked by a piston, and a thin, movable partition can be inserted in the middle of the cylinder to trap the molecule in one half of the cylinder or the other *[see* illustration on opposite *page].* The engine is also equipped with devices for finding which half of the apparatus the molecule is in and a memory for recording that information.

The engine's cycle consists of six steps. in the first step the partition is inserted, trapping the molecule on one side or the other. Szilard argued that the work necessary to insert the partition can in principle be made negligibly small.

In the next step the engine determines which half of the apparatus the molecule has been trapped in. The engine's memory device has three possible states: a blank state to signify that no measurement has been made, an L to signify that the molecule has been observed in the left half of the apparatus, and an R to signify that the molecule has been observed in the right hall When the measurement is made, the memory switches from the blank state to one of the other two.

The third step, which might be called a compression stroke, depends on the knowledge gained during the preceding step. The piston on the side that does not contain the molecule is pushed in until it touches the partition. Unlike the compression stroke of an internal-combustion engine, this compression stroke requires no work, because the piston is "compressing" empty space; the molecule, which is trapped on the other side of the partition, cannot resist the piston's movement.

Then, in the fourth step, the partition is removed, allowing the molecule to collide with the piston that has just been advanced. The molecule's collisions exert a pressure on the face of the piston.

In the fifth step, which might be called the power stroke, the pressure of the molecule drives the piston backward to its original position, doing work on it. The energy the molecule gives to the piston is replaced by heat conducted through the cylinder walls from the environment, and so the molecule continues moving at the same average speed. The effect of the power stroke is therefore to convert heat from the surroundings into mechanical work done on the piston.

In the sixth step the engine erases its memory, returning it to the blank state. The engine now has exactly the same configuration it had at the beginning of the cycle, and the cycle can be repeated.

Overall, the six steps appear to have converted heat from the surroundings into work while returning the gas and the engine to the same state they were in at the start. If no other change has occurred during the cycle of operation, the entropy of the universe as a whole has been lowered. In principle the cycle can be repeated as often as the experimenter wants, leading to an arbitrarily large violation of the second law.

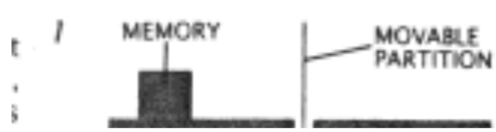
Szilard's way out of this predicament was to postulate that the act of measurement, in which the molecule's position is determined, brings about an increase in entropy sufficient to compensate for the decrease in entropy brought about during the power stroke. Szilard was somewhat vague about the nature and location of the increase in entropy, but in the years after he published his paper a number of physicists, notably Leon Brillouin (the author, in 1956, of the widely read book *Science and Information Theory)* and Denis Gabor (best known as the inventor of holography), tried to substantiate the postulated irreversibility of measurement. In particular they tried to determine what the cost should be, in terms of energy and entropy, of observing a molecule by aiming light at it and observing the reflections.

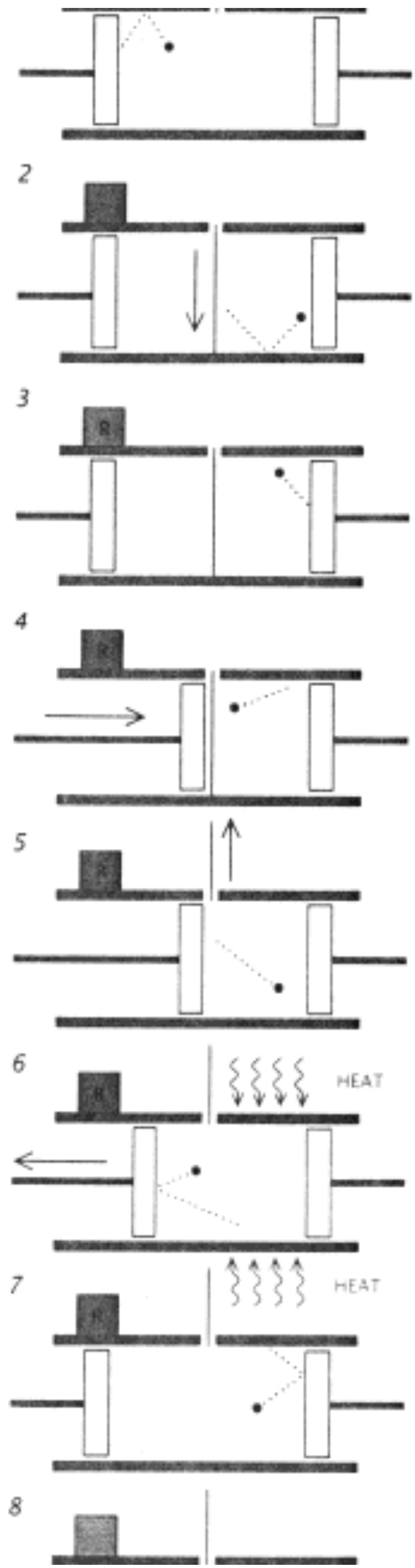
In their work, Brillouin and Gabor drew on a theory that had been developed since Maxwell's time: the quantum theory of radiation. According to the classical wave theory of light (to which Maxwell made fundamental contributions), the energy of a light ray can be made arbitrarily small. According to the quantum theory, however, light consists of energy packets called photons. The energy of a photon depends on its wavelength, or color, and it is impossible to detect less than one photon of light. Brillouin argued that for a molecule to be observed it must scatter at least one photon of a probe beam, and that when the photon's energy is dissipated into heat, the dissipation must produce an entropy increase at least as great as the entropy decrease Szilard's engine could achieve as the result of information gained about the scattering molecule.

Why not simply use a probe beam of photons that have very low energies? The scheme will not work, because of another, more complicated, consequence of the quantum theory. According to the quantum theory of radiation, any vessel whose walls and interior are all at a single constant temperature becomes filled with a "gas" of photons: a bath of radiation. The wavelengths of the photons depend on the temperature of the vessel. Such a photon gas constitutes the uniform red or orange glow inside a hot furnace. (At room temperature the photons are mostly in the infrared part of the spectrum and are therefore invisible.)

The photon gas might seem at first to be a handy source of light by which the demon could observe gas molecules (thereby saving itself the entropy cost of a flashlight). One of the surprising consequences of the second law, however (a consequence discovered by Gustav Robert Kirchhoff in 1859), is that it is impossible to see anything in a vessel at uniform temperature by the light of the vessel's own glow. If one looks into a kiln in which pots are being fired, for example, one will see a uniform orange glow almost devoid of contrast, even though the pots in the kiln may have very different colors, brightnesses and surface textures.

The objects in the hot kiln look as if they are all the same color and brightness, but they are not, as one can verify by shining a bright light on them from outside the kiln. The reason the objects nearly disappear by the light of the kiln must therefore be that dark (that is, nonreflective) objects glow proportionately more brightly than light (reflective) objects, so that the total light intensity leaving any object (reflected and emitted light combined) is the same.

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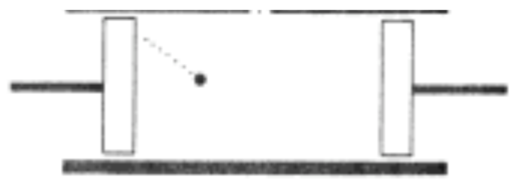
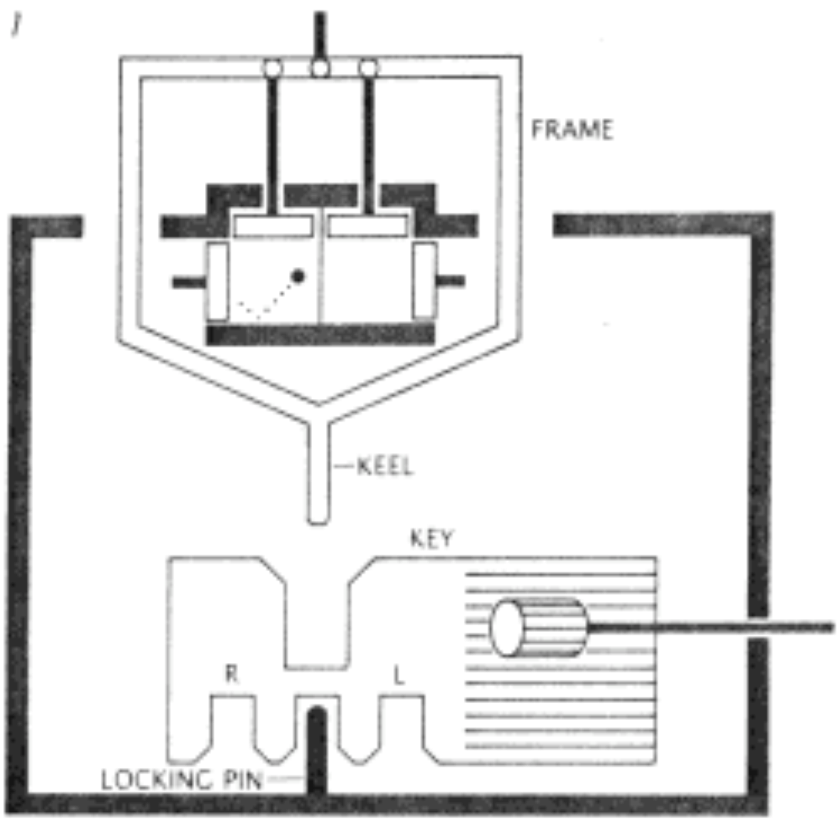


Szilard Engine. modeled after a machine described in 1929 by Leo Szilard, seems to convert heat from its surroundings into work contrary to the second law. The engine (1) is a cylinder that is blocked off at both ends by pistons; it is equipped with a movable partition and devices for observing the cylinder's contents and recording the results of observations. The cylinder contains a single molecule. At the start of the engine's cycle (2) the partition is lowered, trapping the molecule in one half of the cylinder. The observational devices determine and record which half contains the molecule (3). and the piston from the other half is pushed in until it touches the partition (4). Moving the pis ton requires no work since it compresses empty space. Then the partition is withdrawn (5) and the molecule strikes the piston, pushing it backward (6). (The one-molecule gas "expands" against the piston.) Energy lost by the molecule as it works against the piston is replaced by heat from the environment. When the piston has returned to its original position (7). the memory is erased (8) and the cycle can begin again.



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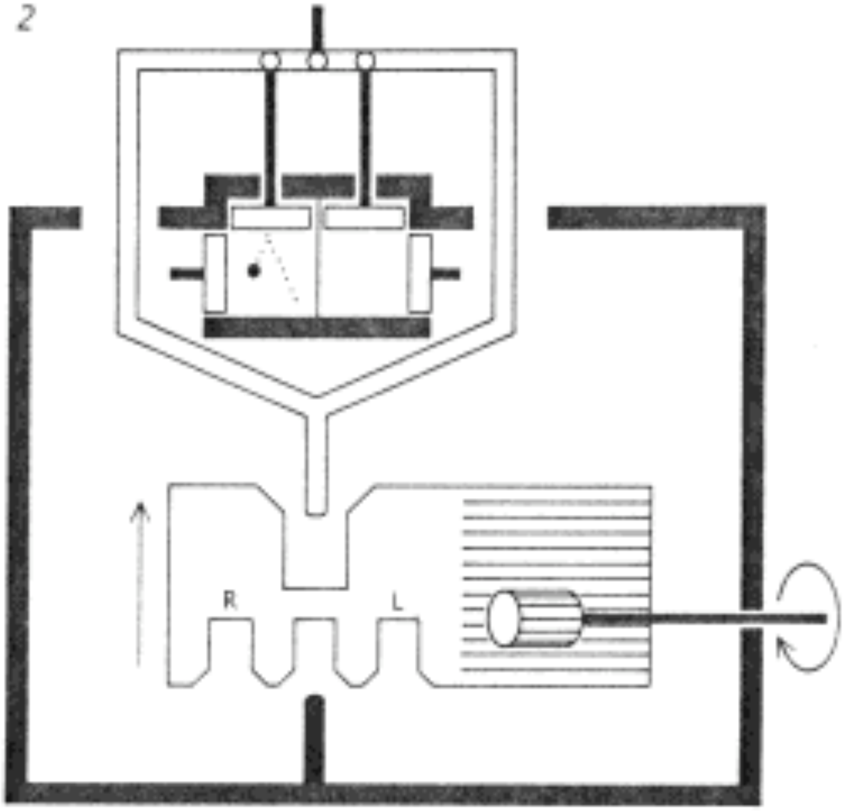

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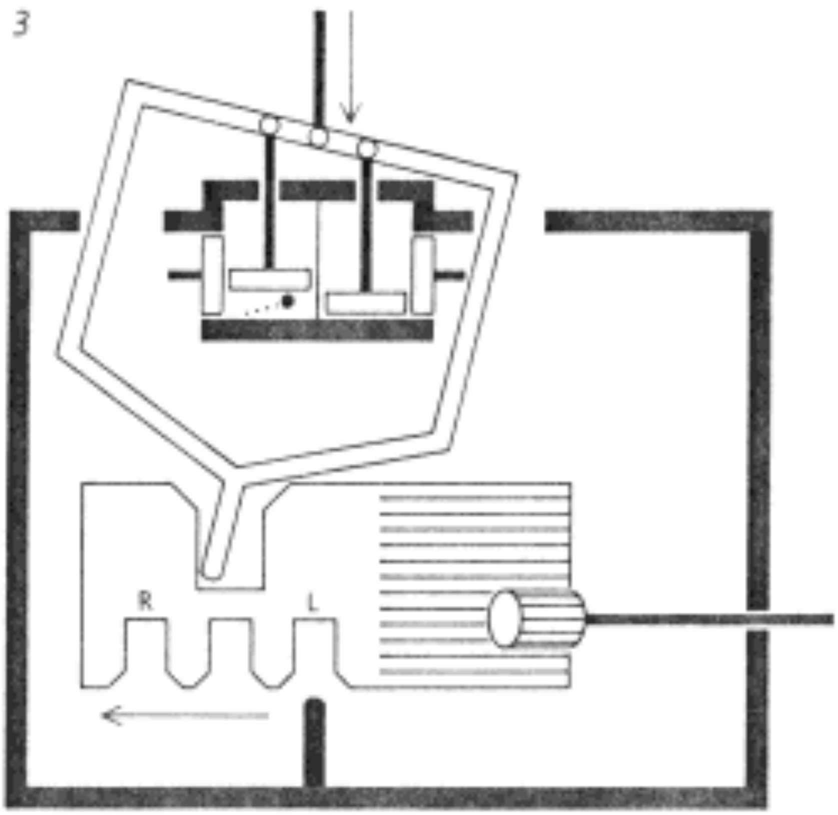

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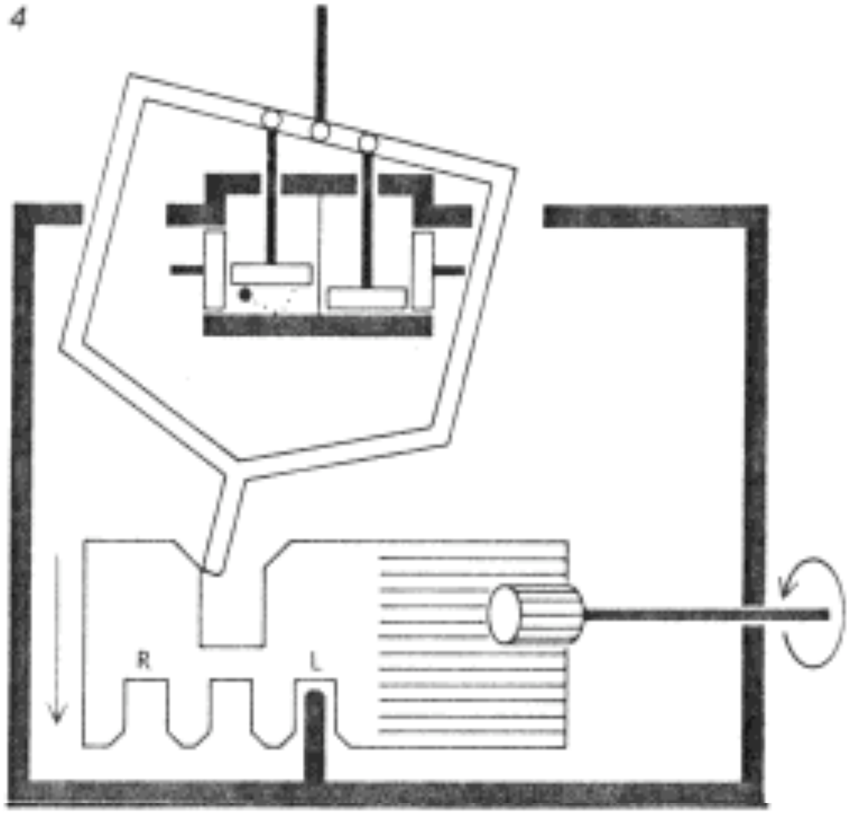

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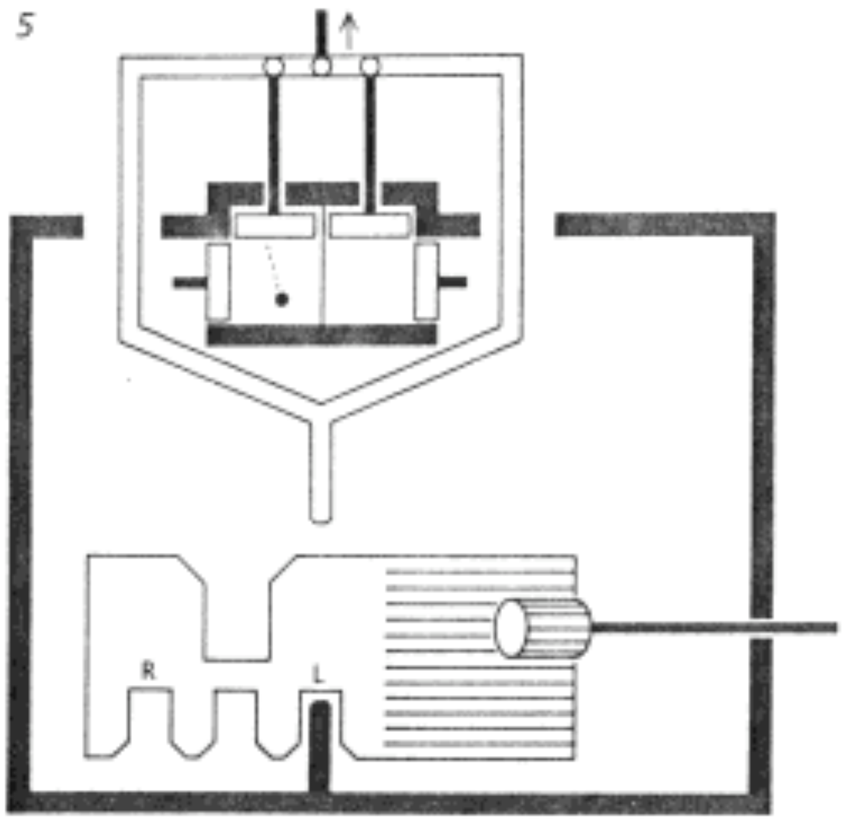

Measurement apparatus, designed by the author to fit the Szilard engine, determines which half of the cylinder the molecule is trapped in without doing appreciable work. A slightly modified Szilard engine sits near the top of the apparatus (1) within a boat-shaped frame; a second pair of pistons has replaced part of the cylinder wall. Below the frame is a key, whose position on a locking pin indicates the state of the machine's memory. At the start of the measurement the memory is in a neutral state, and the partition has been lowered so that the molecule is trapped in one side of the apparatus. To begin the measurement (2) the key is moved up so that it disengages from the locking pin and engages a "keel" at the bottom of the frame. Then the frame is pressed down (3). The piston in the half of the cylinder containing no molecule is able to descend completely, but the piston in the other half cannot, because of the pressure of the molecule. As a result the frame tilts and the keel pushes the key to one side. The key, in its new position. is moved down to engage the locking pin (4), and the frame

is allowed to move back up (5). undoing any work that was done in compressing the molecule when the frame was pressed down. The key's position indicates which half of the cylinder the molecule is in, but the work required for the operation can be made negligible To reverse the operation one would do the steps in reverse order.

To see why this strange leveling of intensity must take place, suppose it did not occur and think about the consequences for the second law. Suppose two objects, say a vase and a pot, are placed close together in a kiln at uniform temperature. If the intensity of light leaving the vase toward the pot were greater than that leaving the pot toward the vase, energy would flow from the vase to the pot. The pot would become warmer and the vase would become cooler.

Thus, without the expenditure of work, two regions that were once at a uniform temperature would come to different temperatures, just as it a Maxwell's demon had been sitting between them, and the second law would be violated. Therefore if the second law is to be valid, objects in a vessel at uniform temperature cannot have different surface intensities.

in order to see the objects in a furnace, then, one must shine light in from an external source, such as a flashlight that has a filament hotter than the furnace's temperature. In daily life such light sources-the sun, for example-make it possible for us to see objects in vessels that are uniformly at room temperature.

Brillouin, Gabor and others, armed with an understanding of the photon gas, argued that Maxwell's demon cannot observe the molecules it sorts without some kind of light source. Therefore, they said, the demon can not violate the second law. Every time it observes a molecule the demon must dissipate the energy of at least one photon; the energy of that photon must be greater than a minimum energy determined by the temperature of the gas in which the demon sits. Such arguments, although they are not completely rigorous, seemed to substantiate Szilard's belief that acquiring a given amount of information entails producing a corresponding amount of entropy.

The next major progress toward banishing the demon was a side effect of research by Rolf Landauer of IBM on the thermodynamics of data processing. Certain data-processing operations, such as the copying of data from one device into another, are analogous to measurements, in that one device acquires information about the state of the other. Hence it was generally believed in the 1950's that data-processing operations were intrinsically irreversible (in the thermodynamic sense of the word), just as Szilard had argued that measurement in general is irreversible. It was thought that any kind of data operation required the generation and removal of at least one bit's worth of heat for every bit of data to be processed. (This is an extremely small quantity of heat: roughly one ten-billionth of the heat actually generated by existing electronic circuits.)

In about 1960 Landauer analyzed the question more thoroughly. He found that some data operations are indeed thermodynamically costly but others, including, under certain conditions, copying data from one device to another, are free of any fundamental thermodynamic limit I see "The Fundamental Physical Limits of Computation," by Charles H. Bennett and Rolf Landauer; SCIENTIFIC AMERICAN July, 1985.

Landauer's proof begins with the premise that distinct logical states of a computer must be represented by distinct physical states of the computer's hardware. For example, every possible state of the computer's memory must be represented by a distinct physical configuration (that 'is, a distinct set of currents, voltages, fields and so forth).

Suppose a memory register of n bits is cleared; in other words, sup-pose the value in each location is set at zero, regardless of the previous value. Before the operation the register as a whole could have been in any of 2" states. After the operation the register can be in only one state. The operation has therefore compressed -many logical states into one, much as a piston might compress a gas.

By Landauer's premise, in order to compress a computer's logical state one must also compress its physical state: one must lower the entropy of its hardware. According to the second law, this decrease in the entropy of the computer's hardware cannot be accomplished without a compensating increase in the entropy of the computer's environment. Hence one cannot clear a memory register without generating heat and adding to the entropy of the environment. Clearing .a memory is a thermodynamically irreversible operation.

Landauer identified several other -operations that are thermodynamically irreversible. What all these -operations have in common is that they discard information about the computer's past state. In Landauer's phrase, such operations are "logically irreversible."

The connection of these ideas to the problem of the measurement, implicit in Landauer's work and in the reversible models of computation developed during the 1970's by Edward Fredkin of M.I.T., myself and others, became explicit in

1982, when I proposed that they provide the correct explanation of Maxwell's demon. Consider the operating cycle of Szilard's engine. The last step, in which the engine's memory is reset to a blank state, is logically irreversible, because it compresses two states of the machine's memory ("'The molecule is on the left" and "The molecule is on the right") into one ("The molecule's position has not yet been measured"). Thus the engine cannot reset its memory without adding at least one bit of entropy to the environment. This converts all the work that had been gained in the power stroke back into heat.

What about the measurement step? Is it thermodynamically costly as well? In that case the engine would add to the entropy of the universe twice: once in measuring the molecule's position and again in resetting its memory after the power stroke. Actually the measurement does not have to be thermodynamically costly. There are ways to observe molecules other than by bouncing light off them. To prove this point I have designed a reversible measuring device, which measures and records the position of the molecule without undergoing any thermodynamically irreversible steps.

We have, then, found the reason the demon cannot violate the second law: in order to observe a molecule, it must first forget the results of previous observations. Forgetting results, or discarding information, is thermodynamically costly.

If the demon had a very large memory, of course, it could simply remember the results of all its measurements. There would then be no logically irreversible step and the engine would convert one bit's worth of heat into work in each cycle. The trouble is that the cycle would not then be a true cycle: every time around, the engine's memory, initially blank, would acquire another random bit. The correct thermodynamic interpretation of this situation would be to say the engine increases the entropy of its memory in order to decrease the entropy of its environment.

Attributing the gain in entropy to the resetting step rather than to the measurement step may seem to be a mere bookkeeping formality, since any complete cycle of Szilard's engine must include both steps, but considerable confusion can be avoided if one draws a clear distinction between the acquisition of new information and the destruction of old information. The confusion may or may not have existed in Szilard's mind. In most of his paper he refers to measurement as the irreversible step, but at one point he makes an accounting of entropy changes during the cycle and finds, without explicitly commenting on it, that the increase in entropy takes place during the resetting of the memory.

If subsequent workers had pursued this aspect of Szilard's paper, they would have come to our present understanding of Maxwell's demon. Their failure to do so is an irony in the history of science: the advancement of one branch of physics (the quantum theory of radiation) apparently delayed progress in another branch (thermodynamics). One aspect of quantum mechanics that reinforced the idea that a fundamental thermodynamic price must be paid for acquiring information is the uncertainty principle, which holds that certain sets of measurements cannot be carried out with more than a certain degree of precision. Although the uncertainty principle sounds similar to Szilard's hypothesis that measurements have an irreducible entropy cost, in fact it is fundamentally different. Szilard's hypothesis concerns the thermodynamic cost of measurements, whereas the uncertainty principle concerns the possibility of their being made at all, whatever their thermodynamic cost.

Another source of confusion is that we do not generally think of information as a liability. We pay to have newspapers delivered, not taken away. Intuitively, the demon's record of past actions seems to be a valuable (or at worst a useless) commodity. But for the demon "yesterday's newspaper" (the result of a previous measurement) takes up valuable space, and the cost of clearing that space neutralizes the benefit the demon derived from the newspaper when it was fresh. Perhaps the increasing awareness of environmental pollution and the information explosion brought on by computers have made the idea that information can have a negative value seem more natural now than it would have seemed earlier in this century.

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