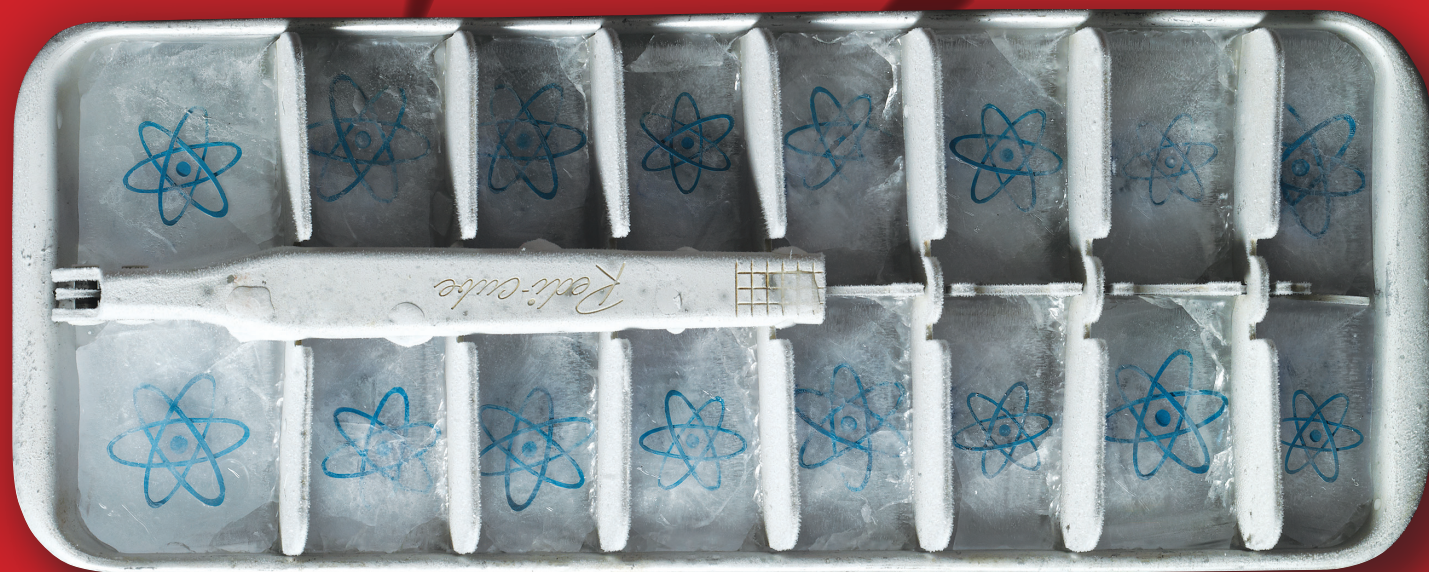


Special Feature

Maxwell's Demons Appear in the Lab

The 19th century Demon who posed a challenge to
a fundamental law of thermodynamics
has reappeared in 21st century labs.
It exploits information to convert heat into work

By Charles H. Bennett and Benjamin Schumacher



Adam Voorhes

A creature born in the mind of 19th century Scottish physicist James Clerk Maxwell has been summoned and put to work in laboratories both in the US and Japan. The creature, called Maxwell's Demon, became famous because it seems at first as if it could turn heat into work without causing any other change, which would violate the Second Law of thermodynamics and realize a perpetual motion machine. Of course the demon cannot violate the Second Law, but you shouldn't get disappointed. In understanding why it cannot, we learn a lot about the fundamental laws of physics and information and the relation between them.

Challenge the Second Law

Before going into the story, let us explain what heat is. A gas is swarm of trillions upon trillions of molecules, flying through empty space and colliding with each other and the walls of the container. The molecular motion is extremely disorganized and is related to the temperature of the gas. If we increase the temperature of the gas, the average speed of the molecules increases. But at any given moment there are molecules in all parts of the container, faster molecules and slower molecules, molecules moving in every direction. Only if we take a large-scale statistical view, not spotting molecules one by one, does the gas seem simple and uniform.

To visualize this, imagine a courtyard surrounded by high walls. Within the courtyard, thousands of basketballs bounce around. The balls represent the molecules. Unlike macroscopic basketballs, however, these do not lose energy and slow down from friction. Friction is a large-scale, statistical phenomenon; on the microscopic scale, the molecules can only exchange energy with each other in collisions. The courtyard of balls is a chaos of unending movement.

On their own, at random, the swarm of balls will tend to spread themselves throughout the courtyard. But suppose that a fence runs

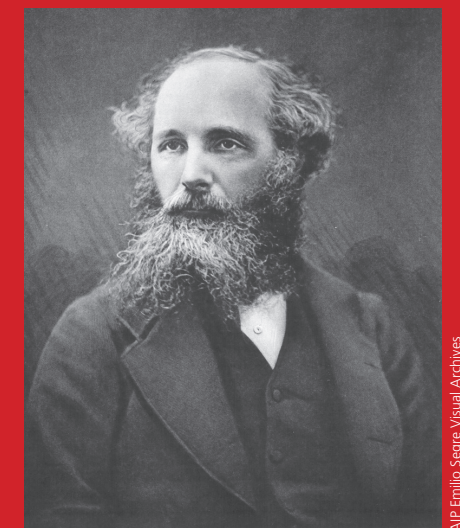
down the middle of the courtyard, with a gate in the center. If the gate is closed, the balls cannot cross the fence. If we open the gate, the balls can pass through the opening. Soon, there are just as many balls on one side as on the other, and balls fly through the gate in both directions equally often.

What if we wish to gather the balls on one side of the gate? One way to do this is to slowly move one of the outer walls toward the fence, then shut the gate once all the balls have been forced through. However, pushing the outer wall inward against the pressure of the bouncing balls requires doing physical "work", which adds energy to the balls, increasing their temperature.

Maxwell imagined a different method using a being that soon came to be called "Maxwell's demon". Since the balls fly in all directions, by chance some of the balls are sometimes moving in the way we want. His "demon" simply waits at the gate and watches. When a ball approaches from the left, the demon opens the gate so the ball passes through. When a ball approaches from the right, the demon keeps the gate shut and the ball bounces off [see illustrations in next page on the top]. Since the demon never pushes the gate against the balls, it need not do much work — ideally, none at all — to operate the gate. Soon all of the balls are gathered on the right-hand side of the courtyard. The demon has compressed the gas to a smaller volume without doing any work, and therefore without changing its temperature.

Maxwell's demon attracted a lot of attention from physicists since it seems at first to violate a fundamental law. Once the demon compresses the gas, the gas can be expanded again, as in the cylinder of an engine, to do useful work. The demon has turned heat (the thermal motion of the gas) into work with no other result — a direct violation of the Second Law of Thermodynamics.

Maxwell's demon is an imaginary supernatural creature, so its magical power



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James C. Maxwell Father of the Demon. He formalized four equations which describe electrodynamics, for which he often appears in textbooks. He also found electromagnetic waves propagate at the speed of light, and studied statistics of motion gas particles. He was born in 1831, died in 1879.

to violate the Second Law is no real surprise. But could a real, physical "demon" accomplish the same task? That is the question that has fascinated physicists ever since Maxwell's day. They have approached the question in two different ways.

The Demon as a Simple Machine

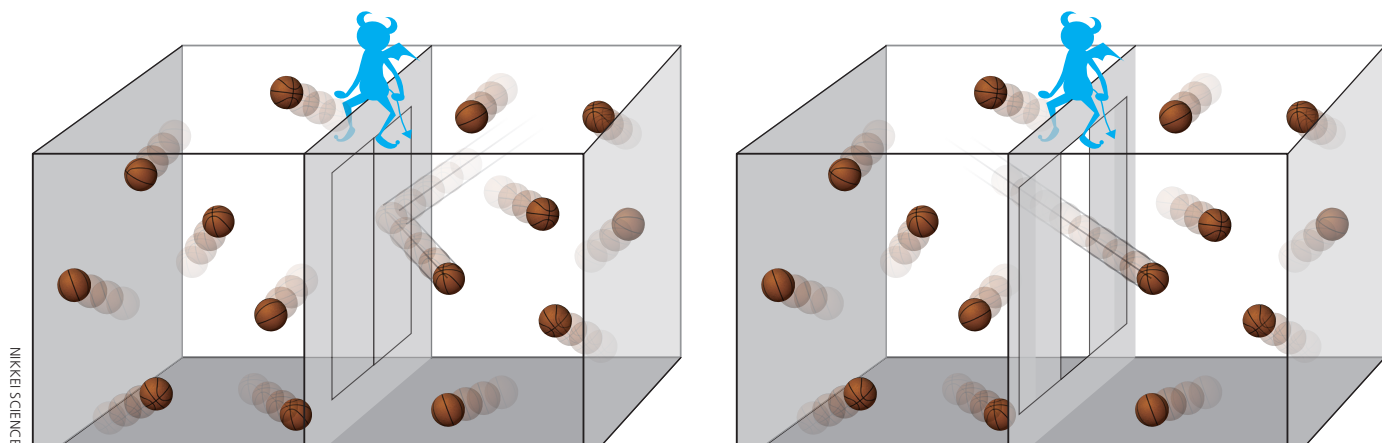
The first approach is to replace the magical demon with a simple mechanical device. The pioneer of this approach was Marian Smoluchowski, a Polish physicist of a hundred years ago. Here is how his idea looks in our courtyard of bouncing balls. Again, a fence divides our courtyard into two halves. A lightweight gate in the fence is designed to swing in only one direction, and the hinge has a spring that tends to push the door closed. The spring keeps the gate shut. When a ball strikes the gate moving from the left, it pushes the gate open and the ball passes through to the right. [see an illustration in next page in the bottom]. But when a ball strikes it from the right, it bounces off the shut gate and stays on the right side of the courtyard. Soon the balls gather on the right-hand side. The one-way gate seems to work just like Maxwell's demon.

However, Smoluchowski pointed out that this argument is fundamentally flawed. Remember, on the microscopic scale there is no friction, even for the gate. When the

KEY CONCEPT

Does Demon violate the Second Law?

- The Demon that Scottish physicist Maxwell proposed appears to convert heat to work without making any other change. If it is true, the Demon violates the Second Law of Thermodynamics and enables perpetual motion machine.
- Two research groups, one in Japan and the other in the US, physically realized Maxwell's Demon independently. Their Demon didn't violate the Second Law.
- Demons seem to violate the Second Law if one ignores the information they acquire. Information always is stored in something physical, like a semiconductor memory or photons of light. Taking the acquisition and destruction of this information into account saves the Second Law, as recent experiments have shown.



One Way! A Demon opens the gate when a ball is approaching from the left, and let it pass through to the right. He closes the gate when a ball is approaching from the right, so that the

ball bounces off. After a while, all balls gather in the right side. Releasing the fence, it is pushed to left by the bouncing balls. The Demon converts thermal motion of balls into work.

spring pushes the opened gate shut, it must simply bounce open again. Very soon, after being struck by a few flying balls, the gate will swing open and shut in a quite disorderly way, participating in the thermal motion of the system. Now it is no longer a one-way gate at all. It sometimes allows a ball to pass from the right, by swinging shut against one that has wandered in front of it from the right side while it is open. This knocks the ball to the left side of the courtyard, in the exact reverse of the gate's intended action. Smoluchowski argued that if the balls and the gate are at the same temperature, it will work backward and forward equally often. As a demon, the spring-loaded gate is a failure.

If we had a way to remove thermal energy from the swinging gate — to keep it cooler than the balls, so that it tended to remain shut most of the time — then the gate would work in the intended one-way fashion. But thermodynamics requires that any cooling system for the gate will require work to operate, and must

expel waste heat into its surroundings. The Second Law will still hold overall.

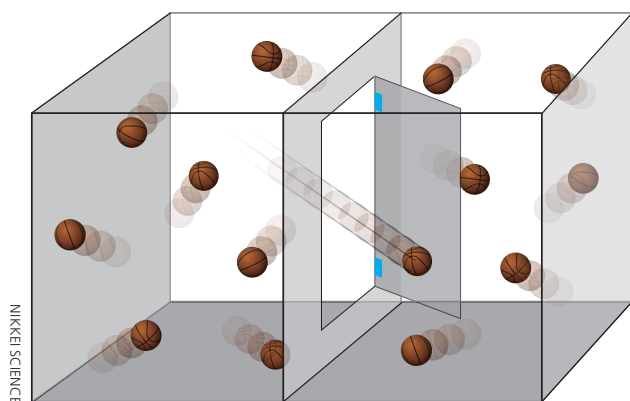
The recent experiments by Mark G. Raizen et al. create a slightly different type of "one-way" mechanism for the atoms in their laboratory. [see "Demons, Entropy, and the Quest for Absolute Zero", by Mark G. Raizen; SCIENTIFIC AMERICAN, March 2011]. To picture it, imagine that our fence is not solid, but made of iron bars spaced a few inches apart, like the fence surrounding a park. Instead of balls, the courtyard is full of flying umbrellas, all initially closed [see illustrations on opposite page on the top]. Because the closed umbrellas are narrow enough, they can fly between the bars of the fence and would distribute themselves equally on both sides, just as the basketballs did. But now suppose that on the right side of the fence, there is a small device that triggers the umbrellas to spring open. Once an umbrella is open, it can no longer pass between the bars, so it must remain on the right.

The opening of the umbrella is an

irreversible process. That is, the umbrella can be sprung open, but there is no mechanism for pulling it closed again. In the Raizen apparatus, the atoms have two different internal electronic states, represented by blue and red colors. An atom switches from blue to red by absorbing a photon of frequency f_1 and emitting a second photon of frequency f_2 . The emitted photons escape, so there are no f_2 photons around to drive the reverse "red to blue" process. Once the atom changes to red, it stays red. In the same way, once a flying umbrella pops open, it stays open. Thus, our initial swarm of closed umbrellas, flying through and on both sides of the bar fence, will eventually become a swarm of open umbrellas, all trapped on the right-hand side. The fence itself works as Demon.

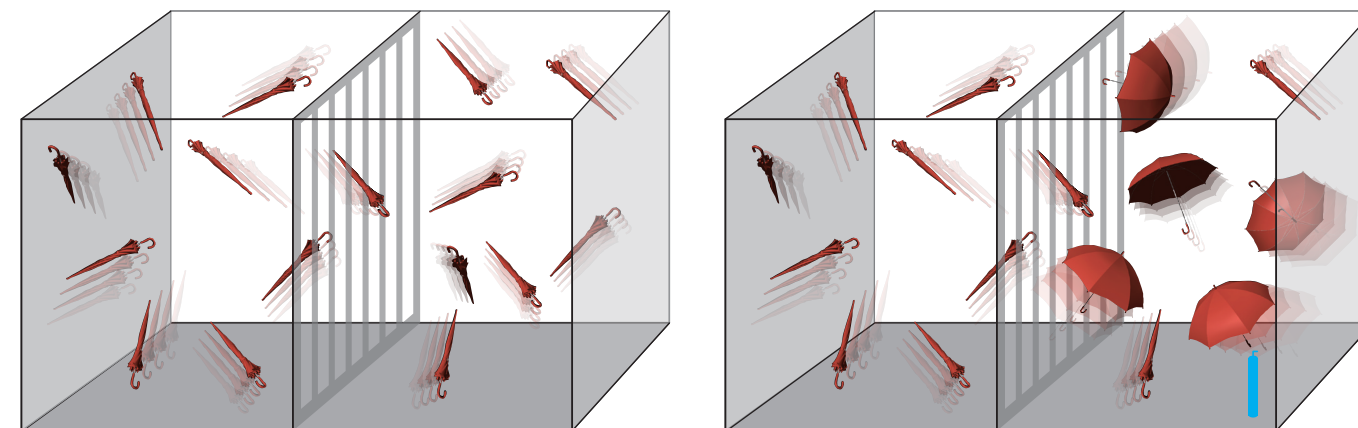
Leaving behind the umbrellas, and returning to Raizen's real world of atoms, we see that after a gas is thus trapped in a small volume in the right side, it can be allowed to expand and do work — and, more crucially for Raizen and his co-workers, lowering its energy in the process. In this way, clouds of extremely cold atoms can be produced.

Raizen's apparatus surely converts random thermal motion of atoms to work, using the one-way gate. Then the Second Law of Thermodynamics is violated? No, it's not the case. The Demon did the conversion, but also brought about other changes to the system. The photon emitted from an atom carries information about the atom, thus taking that information away from the system. Information seems abstract, but in fact it is physical, and physically stored in the photon. Since the Second Law only forbids converting heat into work with no other change in the system, it is not violated by Raizen's experiment. This point is to be reconsidered later.



Swing door acts as Demon?

The answer is No. In the microscopic world with no friction, when the spring-loaded hinges push the opened door shut, the door simply bounces open again. After being struck by a few flying balls, the door will swing open and shut in disorderly way, thus doesn't function as one-way gate.



Change the state One-way gate can be made by changing the state of atoms of a gas, like umbrellas in a courtyard. Closed umbrellas can pass between the bars, but open umbrellas cannot. A device (blue) on the right triggers umbrellas to open. All

umbrellas eventually become open and gather in the right side. If the fence is released, the bouncing umbrellas push the fence to left. The system thus functions as a Demon, who converts thermal motion of umbrellas to work.

The Demon as Robot

There is a second approach to turn Maxwell's fanciful idea into a real device, one that seems more closely related to the "look and decide" strategy of the original. This approach envisions the demon as an information-processing machine — a robot — that acquires information about the system and acts according to some purposeful program. Of course, the robot demon, like everything else in the universe, is subject to the usual laws of physics. In our courtyard of balls, we suppose that a robot is stationed at the gate, programmed to monitor the balls with video cameras and operate the gate as Maxwell's demon would [see an illustration in next page].

Can a robot demon violate the Second Law? It cannot, for a profound reason. Through careful analysis, we conclude that the robot could observe the balls, run its program and operate the gate, all without using any net work. But as it operates, the robot necessarily acquires a memory record of its observations. With billions or trillions of balls, this record might occupy a lot of storage space. This memory record, like the escaping photons in Raizen's experiment, constitutes another physical change in the system, so the demon would have to erase it to actually violate the Second Law. But as the American physicist Rolf Landauer of IBM showed in 1961, regardless of its physical form, the erasure of information requires work. The robot demon must convert a tiny amount of energy into waste heat for each bit of information it wipes out, just enough to preserve the Second Law.

Shoichi Toyabe of Chuo University, Takahiro Sagawa of Tokyo University (Sagawa is now at Kyoto University) and their colleagues recently reported in Nature Physics an experiment which created

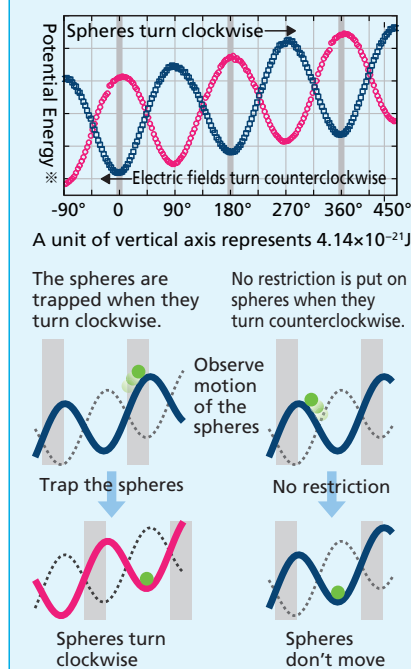
Making a Ball Go Uphill without Pushing It

The experimental setup made by a Japanese group to realize Maxwell's Demon is shown in the right diagram.

The connected microspheres, suspended by molecular tether in water, jiggle randomly because of the thermal motion of water molecules around. Four electrodes on the floor create two kinds of electric fields, both turn counterclockwise as depicted by red and blue arrows. The spheres, being polarized and dragged by the electric fields, incline to turn counterclockwise too. That makes a series of potential hills and valleys going up in the clockwise direction and down in counterclockwise direction, like a spiral staircase with a corrugated spiral ramp instead of stairs.

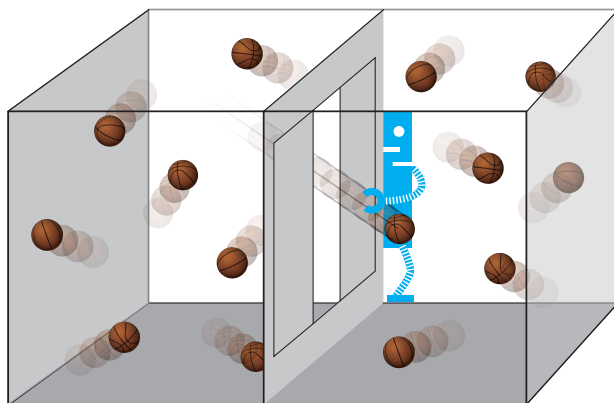
In the experiment, the movement of the spheres was continuously observed by a camera.

When the camera sees that thermal motion has driven the spheres uphill from a potential minimum in the clockwise direction, the equipment immediately switches the electric fields, reversing the phase of the corrugations to trap the molecule in the new location and keep it from falling back, as shown in the bottom diagram. If the molecule tries to move the other way, the electric field is left unchanged. Repeating the process many times the spheres keep moving clockwise up the energy staircase, even though the equipment never pushes them directly. Like sheep dogs herding sheep uphill, the electric fields maneuver the spheres in the desired direction by getting out of their way whenever they try to move uphill, and blocking them whenever they try to move downhill. Thus the energy to move the spheres uphill comes from the water molecules collisions, not from the applied electric fields. The equipment acts as a robot Demon, converting heat into work by observing the spheres' random motion and exerting feedback control over it.



Demon as Robot

If you build a robot that opens and shuts the gate according to the direction of ball's movement, it functions as Demon. But while doing that, the robot stores information of the movement in its memory. Information is physical, equivalent to physical entropy, and the Second Law is saved when you take into account physical properties of the information.



a demon of the "robot" type. In their experiments, a tiny sphere of polystyrene, just big enough to be seen through a microscope, was attached to a base plate by a molecular


tether and suspended in water. The thermal motions of the water molecules knocked the sphere this way and that, producing the random jiggling called "Brownian motion". Electrodes on the base plate created electric fields that established an "uphill" and "downhill" direction in energy terms. The random motion was monitored through a microscope. When the sphere by chance moved in the "uphill" direction, the voltage on the electrodes was adjusted to prevent the sphere from moving backward again. This control procedure, together with the Brownian motion of the sphere, continually maneuvered the sphere around and around in the "uphill" direction without applying any direct push, like a sheep dog maneuvering a sheep, and therefore without doing any work.

What they did in the experiment may seem different, since unlike the story of the basketballs in the courtyard, only one object is being maneuvered. But there is a Demon, which observes aggregated thermal motions of the water molecules and intervenes to move the sphere in an intended way, continually maneuvering it uphill and so converting heat into work. This would be a violation of the Second Law unless some

other change was happening in the system.

Indeed there is another change: Demon's memory record of the movement of the sphere. Toyabe and others did not erase the memory record of their robot demon; indeed instead, they used this record to help analyze the experiment! Furthermore, their observation and control systems used plenty of energy and produced lots of waste heat, far more than an optimal "efficient" demon would need. But the aim of their experiment was not to pose a challenge to the Second Law of Thermodynamics. Their purpose was to demonstrate the ability to control and move a microscopic system by exploiting the thermal fluctuations in its motion, which they achieved.

What Demons Teach Us

In the cooling of Smoluchowski's spring-loaded gate and the memory erasure of the robot, the demon expels waste heat into the environment to restore itself to an orderly state. Even the most efficient device will still be governed by the Second Law of Thermodynamics. Far from challenging this Law, the demons of Raizen et al. and of Toyabe et al. help us to understand it more deeply. The novelty is our increasing ability to understand and use tiny thermal fluctuations of microscopic systems. Raizen and his coworkers used their magneto-optical "simple machine" demon to create clouds of ultra-cold atoms in their laboratory. Sagawa and Ueda in the second research group showed that the behavior of their "robot demon" experiment exactly accords with a recent powerful theoretical relation between work, fluctuations, and information called the generalized Jarzynski equality. Though the experiments may seem very different, both styles of demon exemplify the very same fundamental laws of nature. 

Jarzynski equality now covers Maxwell's Demon

The Jarzynski equality is a theoretical formalism of thermodynamics, proposed by physicist Christopher Jarzynski of Maryland University in 1997. The Second Law of Thermodynamics is in form of inequality, and he rewrote it as an equality by incorporating terms for thermal fluctuation. The Second Law says, for example, "free energy of a system doesn't increase more than the work which is done on the system". In Jarzynski's formalism, the same idea is expressed: "free energy of a system increases by the amount of work done on the system after subtraction of dissipated work due to thermal fluctuation", so that you can calculate how much the free energy increases.

The Jarzynski equality expresses the Second Law in more quantitative way. But in its original form it doesn't take into account a Demon who can actually measure the states of micro-scale system and make a decision based on the measurement results. To solve this problem, Takahiro Sagawa and Masahito Ueda proposed generalized Jarzynski equality in 2010. They added a term for the information that Demon acquired, so that the equality becomes applicable to the system having a Maxwell's Demon inside. (Editors)



Charles H. Bennett and Benjamin Schumacher

Bennett (left) is an IBM Fellow, based on Watson Research Center in New York, though often flying around the world. He is known for proposing the solution to the Maxwell's Demon paradox in terms of memory erasure. He is also an inventor of quantum cryptography and quantum teleportation. Schumacher is professor of Kenyon College. Working on theory of quantum information since early 1980s, he coined "qubit", fundamental unit for quantum information. They both have deep interest in physical aspect of information.

MORE TO EXPLORE

Demons, Engines and the Second Law. Charles H. Bennett in *Scientific American*, Vol. 257, No. 2, pages 68-77; February 1984.

Generalized Jarzynski Equality under Nonequilibrium Feedback Control. Takahiro Sagawa and Masahito Ueda in *Physical Review Letters*, Vol. 104, 090602; March 2010.