Maxwell's Demon: Connecting Thermodynamics, Information, and Life

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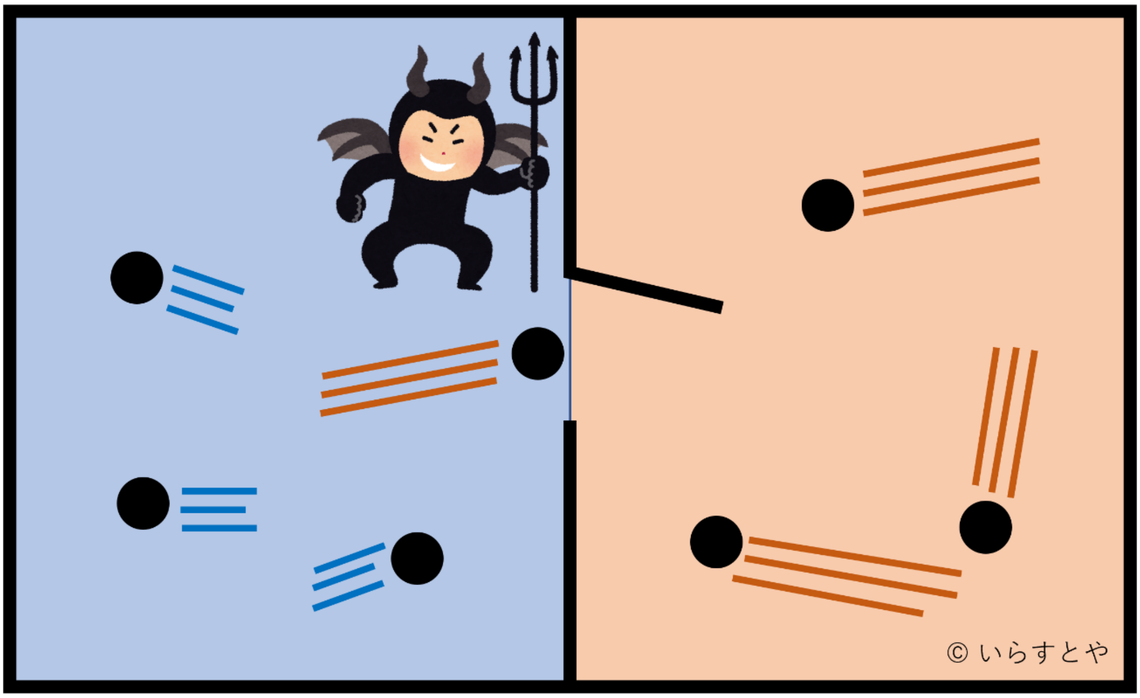

(1)

Imagine you order an iced coffee at the cafeteria on a hot summer day. At first, you are swiping your smartphone and sometimes drinking coffee, however, you gradually forget to drink and got absorbed in your smartphone. When you noticed it, your coffee has already got lukewarm. This is because cold coffee is exposed to the hot air. Generally, if a hot and cold thing is connected, their temperature finally becomes the intermediate constant value. This process is very natural and is one of the principles of thermodynamics.

However, James Clerk Maxwell, a Scottish physicist, suspected that this process does not always occur and proposed a thought experiment in 1871 [1], which seems contrary to this process. Let us suppose a gas permeates a room and it has a uniform constant temperature. The room is divided into two parts, A and B, by a wall with a small hole, and “a demon’’ opens or closes the hole. He can measure the speed of gas molecules and if the molecule passing through the hole from A to B is fast, he opens it, and if slow, he closes it. On the other hand, if the molecule passing from B to A is fast, he closes it, and if slow, he opens it. As a result, fast gas molecules become almost in B and slow ones are almost in A. Faster molecules mean greater kinetic energy, which means higher temperatures. Therefore, in this final state, the gas is separated into A with high and B with low temperatures. This demon creates a temperature difference in one uniform gas! This demon later became known as “Maxwell’s demon”, and it has troubled many physicists.

(2)

To physicists of the time, this thought experiment seemed to violate the principle of thermodynamics. In thermodynamics, the forms of energy transferred between two systems are classified as "work" and "heat," and systems called “heat engines” can convert energy between them. Thermodynamics is based on the principle that no heat engine can convert heat into work with 100% efficiency. However, if we assume that Maxwell’s demons work without external work, we can construct a heat engine that violates this principle, the so-called perpetual motion machine of the second kind.

Let us construct this machine under this assumption. All that is needed is the partitioned room mentioned earlier, the demon, and the gas enclosed in the piston. To separate the hot and cold regions, the demon transfers the heat Q from the cold region to the hot region without external work as we assume. After that, we move the piston into the hot region adiabatically, i.e., without heat exchange to the outside. Then, the heat Q' is transferred to the piston and the gas in it expands and causes mechanical work W externally. After that, the piston is moved to the cold region adiabatically and cooled so that the gas then returns to its original state. Then, the heat Q'-W is transferred from the piston to the cold region because of the conservation of energy of the piston. We can set Q'-W=Q so that the cold region also returns to its original state. To sum up, we can get mechanical work W from only the heat flow between the hot and cold regions. By repeating this, we can completely convert the uniform gas's heat energy into work. This is a perpetual motion machine. This result shook the foundation of thermodynamics.

However, this paradox has now been resolved, because the assumption that the demon does not require external work is false. Let us review the procedure of the demon. First, he measures the speed of a gas molecule and "records" the result somewhere in his memory. Second, he "feedbacks" to the molecule according to the result by opening or closing the hole. Third, he "initializes" his memory. The work we got from a uniform gas is from his feedback. However, recent research has proven that the recording and the initialization need external work [2]. This necessary work is greater than that due to feedback, so the perpetual motion machine cannot be realized.

(3)

The paradox of Maxwell's demon led researchers to consider information processes in the framework of thermodynamics. Now this thought experiment is rethought by using words of information theory, and the new theory called "information thermodynamics" is being established. This theory can handle a wider range of phenomena than traditional thermodynamics.

One application of the theory is to describe biochemical signal transduction in living cells. Signal transduction is the process of transferring a molecule with information through a cell so that living organisms can control their life phenomena in response to environmental changes. For example, E. coli swims in a certain direction by rotating its flagella with flagellar motors. It has the habit of moving in the direction of higher concentrations of food substances, which is called “chemotaxis”. This is a kind of signal transduction that regulates the movement of the flagellum based on the concentration of surrounding substances. In this signaling process, it is performing feedback control like Maxwell’s demon [3]. Therefore, information thermodynamics can be applied to it, and the robustness of the signaling process can be discussed. In this way, information thermodynamics provides a new point of view on life phenomena. It is expected that the robustness, efficiency, and trade-off of living systems can be explained by using this theory.

In this way, questioning common sense, as Maxwell did, can lead to new ways of thinking that no one could have imagined. It is one of the most exciting aspects of science! If you want to enjoy such fun of science, I recommend you become a scientist and do your own research. Then I hope that you will write an essay that will make science interesting to people.

I used DeepL and Grammarly to improve my English expression in this essay.

References

[1] J. C. Maxwell, *Letter to P. G. Tait, 11 December 1867 in Life and Scientific Work of Peter Guthrie Tait,* C. G. Knott (ed.), Cambridge University Press, London, p. 213 (1911).

[2] T. Sagawa, M. Ueda, Phys. Rev. Lett. **102**, 250602 (2009).

[3] S. Ito, T. Sagawa, Nat Commun **6**, 7498 (2015).