The Game of Entropy: the Maxwell's Demon

Guangyu Xu, CID 00813507

June 20, 2014

Abstract

The aim of the project is to simulate the famous thought experiment of the Maxwell's Demon in the form of a simple computer game. The game consists an isolated container of ideal gases with a partition in the middle. The player will act as the demon, trying to separate the faster particles and slower particles by controlling a frictionless sliding door on the partition, thus decreasing the entropy of the system. The possibility that the demon could violate the second law of thermodynamics is then discussed. For a realistic system, the violation could be avoided if a complete analysis is made of the whole system, including the demon itself.

Introduction

The concept of the demon was first published in *Theory of Heat* by J. C. Maxwell in 1872, although at the time he referred it as "a finite being" with "sharpened facilities" [1]. The term "demon" was coincided later when the idea was published on *Nature* in 1874.

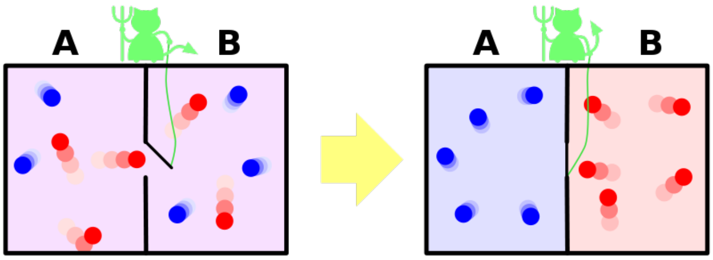

Figure 1: Schematic Diagram of the Maxwell's Demon

> [The second law of thermodynamics] is undoubtedly true as long as we can deal with bodies only in mass, and have no power of perceiving or handling the separate molecules of which they are made up. But if we conceive a being whose faculties are so sharpened that it 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. [...] 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. (J. C. Maxwell, 1872, p. 308)

As suggested by J. C. Maxwell, the demon will create a temperature inequality between portions A and B without the cost of energy, shown in Fig. 1 [1]. Then the temperature difference can be exploited by a steam engine to do work. In such a way, the demon can effectively make a perpetual motion machine by continuously extracting the internal energy of the gas from the surroundings.

[1]Fig. 1 is an image adapted from *Wikimedia Commons* created by Htkym.

Due to the significance of the potential effects brought by the Maxwell's Demon, it has been an infinite source of discussion, which undoubtedly furthered our understanding of the 2rd of thermodynamics. To protect the second law, a variety of reasoning from different perspectives has been proposed to exorcise the demon since its birth.

The Second Law of Thermodynamics

Thermodynamics is the subject of heat, governed by four fundamental laws, namely, the laws of thermodynamics. The laws generalise the relations between energy, heat and work for a thermodynamic system or a thermodynamic process.

Entropy, a state variable, is commonly interpreted as a measure of disorder of the thermodynamic system. Mathematically, it is the number of the specific ways in which the configuration of the system can be reached. For a specific thermodynamic process, the change in entropy turns out to be proportional to the heat transfer divided by temperature, i.e.,

$$\mathrm{d}S = \frac{\mathrm{d}Q}{T}, \tag{1}$$

where $\mathrm{d}S$ is the change in entropy, $\mathrm{d}Q$ is the heat transfer and T is temperature in absolute temperature scale.

The second law of thermodynamics states that the entropy of an isolated system never decreases spontaneously, as such a system always tends to thermal equilibrium, a state of maximum entropy. It essentially places constraints on the direction of heat flow [2]. Considering a system of two objects with different temperatures, if heat flows spontaneously from the colder one to hotter one, then the heat entering the hotter object is the same as the heat leaving the colder one but the drop in entropy for the colder object is greater than the increase of entropy for the hotter one. As a result, the overall entropy of the entire system will decrease, which is in contradiction with the second law of thermodynamics.

However, the second law of thermodynamics is essentially a macroscopic description of a system, as a result of the collective bulk behaviour of a large number of particles. The concern of Maxwell is that the second law only holds for beings that are unable to handle the individual microscopic particles. For intelligent beings like the demon, who is able to resolve the states of all molecules, it would be possible to violate the second law of thermodynamics.

Computational Methods

The thought experiment of the Maxwell's Demon was simulated in a simple game written in Java SE 7 [2] with ACM libraries [3]. For the purpose of playability, some apparently non-physical gaming elements were also added to the game.

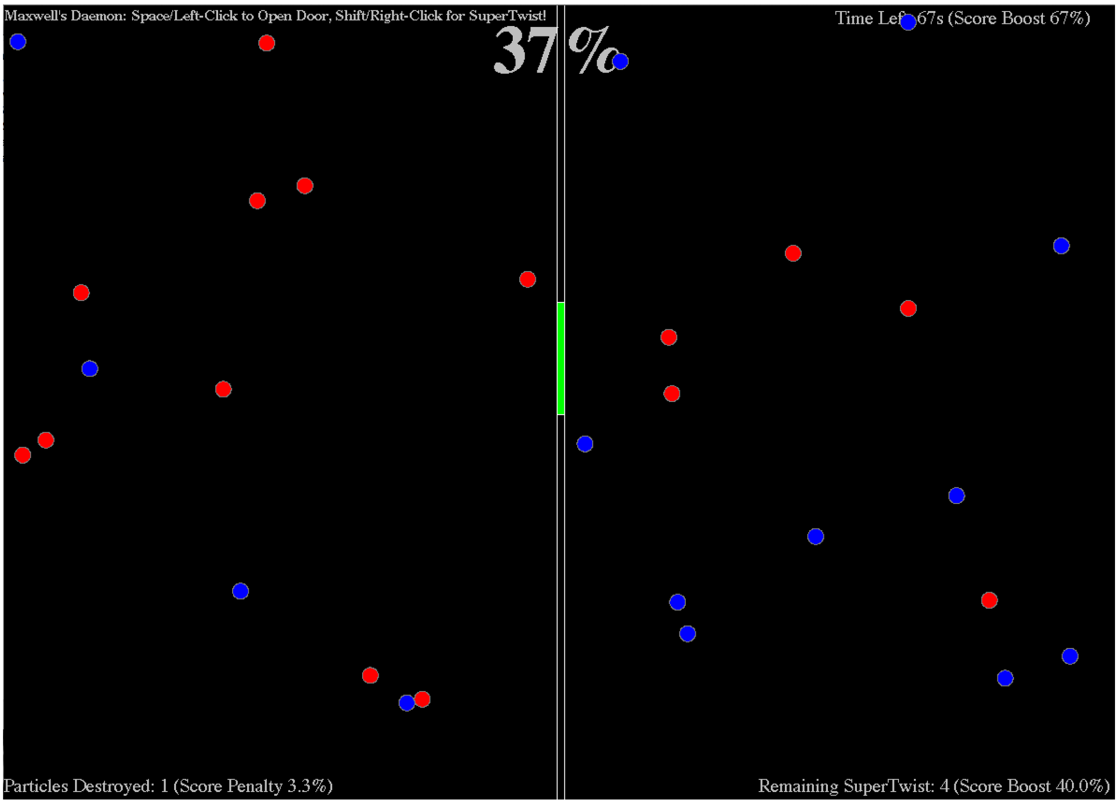

Figure 2: The Screenshot of Maxwell's Demon Game

Shown in Fig. 2, the game consists a simplified version of ideal gases in an isolated container, in which the particles only have two possible states represented by red and blue particles respectively. The red particles have higher speed than the blue ones. There is a partition in the middle with a frictionless sliding door controlled by the player. The target is to separate the red and blue particles into the two divisions by opening and closing the door.

At the initialisation of the game board, all the red and blue particles are created in pairs at random locations with random directions, moving back to back, which simulates the innate random nature of a real thermodynamic system.

[2] Java is the trademark of Sun Microsystems, Inc.
[3] ACM Java Task Force is a library developed by Stanford University.

During the actual gameplay, the procedure in each frame is comprised of three steps. The first step is for all particles to move a small step further. Then the algorithm of checking for all possible collisions of the particles with the container walls and the partition is executed. The collisions between the particles themselves are ignored by the assumption for an ideal gas. Whenever a particle strikes an obstacle, the velocity is reversed in the direction perpendicular to the collision surface. The final step in one frame is to update the statistics of the game, i.e., the percentage progress, score multipliers and timing information. The percentage progress is calculated via the ratio of red and blue particles in each one of the divisions, in such a way that 100% is reached when there is no red particle on the left side and no blue particle on the right side, or other way round.

Since the partition cannot be made infinitely thin for visibility purpose, there is always a possibility that a particle gets stuck in the door when it shuts. To prevent this scenario, the particle will be destroyed, although it is obviously in contradiction with mass conservation.

Another undesirable scenario is when a particle has little horizontal component of velocity, which makes it almost impossible to pass the sliding door. To assist the player to get out of this scenario, a cheating method called "super twist" is built, which simultaneously rotates all particles by $90\,^{\circ}$. Apparently no real physical machinery is able to do so.

Each round of the game ends when either 100% progress is reached or $100sec$ has elapsed; then the final score is displayed with greetings. The player is considered to successfully break the law of physics only if the game progress is over 15%, because small fluctuations of the entropy are inherently allowed in nature.

Exorcism and Discussion

In 1929, Leó Szilárd, a Hungarian-American physicist, suggested that no realistic being could do the job of the demon. He argued that for the demon to be able to allow the particles to selectively pass the door, the necessary measurements of the states of the particles could not be made without consuming enough energy to cause an increase in entropy sufficient to prevent the violation of 2rd law [3]. For the game created in this project, the second law cannot be violated because the player, as a part of the system, is indeed paying a lot of effort to observe the particles.

However, after the advent of information theory [4], an exception of this argument was raised in 1960 by Rolf Landauer from IBM research division. He proved that it is possible to determine the state of the particles using thermodynamically reversible processes, which do not increase the entropy [5]. However, according to the principle of Landauer, any logically irreversible manipulation of information, such as erasure of data, must be accompanied by an increase in the entropy of the surrounding of that processing device [6]. In analogy to a computer, the demon must have a memory device that stores the information about the measured states of the particles. As long as the information is not erased, it is possible to lower the entropy of the system at the cost of the demon's memory. But a finite being cannot possess infinitely large memory, which means at some point all the old information must be cleared, resulting in an increase of the entropy. So the second law is again protected from the demon.

In fact, there is a major failure in the exorcism via information theory. The principle of Landauer is essentially a logic deduction from the second of thermodynamics. For a memory device of n bits, the distinct logic states must be represented by distinct physical states, e.g., distinct sets of voltages, currents, etc. This is the way how information entropy is connected to thermodynamic entropy. When the information stored in the memory is erased, all the distinct logical states of each bit as well as physical states of the hardware are set identical. The entropy of this device is lowered because there is only one way to have all bits in the same state. By the second law of thermodynamics, the entropy of the environment must be increased to compensate for the drop of entropy of the memory device [7].

Since the principle of Landauer is deduced by the second law and then the principle is used to prevent the violation of the second law, the exorcism is apparently a circular proof [8]. There is no way to exorcise the demon by assuming that the demon is already governed by the second law.

Conclusion

The project aims to visualise the thought experiment of the Maxwell's Demon in a computer game. The player is unable to violate the second law of thermodynamics in this game, as the player is consuming a lot of energy to observe the particles. In reality, there is by far no known being that behaves like the demon. However, the existence of the Maxwell's Demon can never been falsified because it is just a hypothetical being that *could* violate the second law.

Bibliography

[1] Maxwell, James Clerk. *Theory of Heat.* Longmans, Green and Co., 1872.

[2] Georgia State University. "Second Law of Thermodynamics." *HyperPhysics*, 17 Jun 2014 [4].

[3] Szilard, Leo. "On the decrease of entropy in a thermodynamic system by the intervention of intelligent beings." *Maxwell's Demon 2: Entropy, Classical and Quantum Information, Computing* (1923): 110-119.

[4] Shannon, C. E. "A Mathematical Theory of Communication." *Bell Sys. Tech. J.* 27: 379-423.

[5] Bennett, Charles H. "Demons, engines and the second law." *Scientific American* 257.5 (1987): 108-116.

[6] Bennett, Charles H. "Notes on Landauer's principle, reversible computation, and Maxwell's Demon." *Studies In History and Philosophy of Science Part B: Studies In History and Philosophy of Modern Physics* 34.3 (2003): 501-510.

[7] Bennett, Charles H., and Rolf Landauer."The fundamental physical limits of computation." *Scientific American* 253.1 (1985): 48-56.

[8] Earman, John, and John D. Norton. "Exorcist XIV: The wrath of Maxwell's demon. Part II. From Szilard to Landauer and beyond." *Studies In History and Philosophy of Science Part B: Studies In History and Philosophy of Modern Physics* 30.1 (1999): 1-40.

Appendix: Programming Scripts

[4] http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/seclaw.html