How Information Engine works and Experimental Realizations of Information Engine

Kuen Wai Tang
Department of Physics, UC Davis
Email address: tkwtang@ucdavis.edu

9th June 2022

Abstract:

In this project, I did literature review to understand how the Szilard engine works and the meaning of Landauer's Principle. I also found some experimental realization of the Szilard engine to show that the Szilard engine is not just some thought experiment, but we can really build it.

A. Introduction

In Phy 256B, I learnt that information can be used as fuel for the engine. I think this topic is interesting and I want to understand more on how information works and how to build an information engine, therefore, I did literature review to understand how the Szilard engine works and some experimental realization of the Szilard.

B. Second Law of Thermodynamics and Heat engine

In 1871, James Clerk Maxwell proposed a thought experiment to illustrate the possibility of violating the second law. In his thought experiment, a box with a wall at the center is filled with gas molecules. A trap door is on the wall and allows the gas molecules to move from one partition of the box into the other. The initial temperature of the two partitions are the same because the average speed of the gas molecules are the same. Now, imagine there is a demon inside the box that can (i) monitor the speed of the speeds of the gas molecules inside the box, and (ii) open or close the trap door.

Suppose a gas molecule in the right partition approaches the trap door. The demon measures the speed of the gas molecule. If the speed is higher than the threshold speed v_0, then the demon will open the trap door and allow the molecule to move from the right partition to the left partition. If the speed of the molecule is lower than v_0, then the demon will close the trap door so that the low speed molecule will remain in the left partition. (Fig. 1)

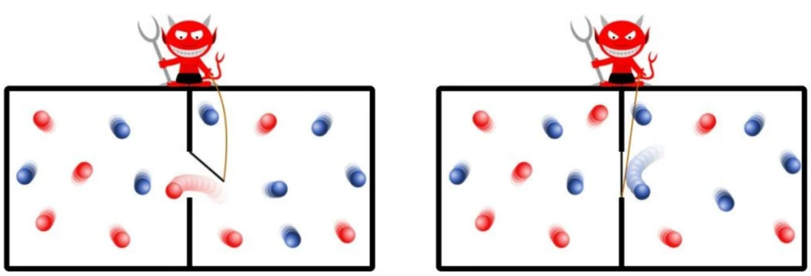

Figure 1: The demon can control the trap door and sort the particles according to their speed.

After some time, all the gas molecules with speed higher (lower) than v_0 will be all in the left (riight) chamber (Fig. 2). As the average speed of the molecules in Chamber A is higher than that of the molecules in Chamber B, the temperature of Chamber A is now higher than that of Chamber B. The box can work as a heat engine. However, this process violates the second law of thermodynamics. When a high speed molecule moves from Chamber B to Chamber A, it carries a small amount of heat dQ. The change in heat in Chamber B is -dQ and that in Chamber A is +dQ. Therefore, the net change of entropy of the system is

$$\begin{aligned} dS &= dS_C + dS_H \\ &= -\frac{dQ}{T_C} + \frac{dQ}{T_H} \end{aligned},$$

where dS_C is the change of the entropy of Chamber B and dS_H is the change of the entropy of Chamber A. T_C and T_H are the temperatures of Chamber B and Chamber A respectively. Since $T_C < T_H$, the magnitude of the first term is larger than that of the second term. The change of entropy is negative.

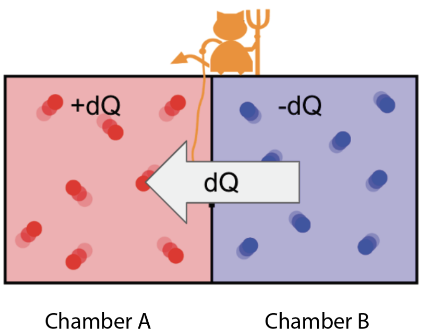

Figure 2: All the high speed particles are in Chamber A and all the low speed particle are in Chamber B. Chamber A is at a higher temperature than Chamber B.

Maxwell thought that humans could not violate the second law because humans did not have the ability to control the movement and monitor the information of individual molecules. However, if a demon who can control and monitor individual molecules, it may be possible for it to violate the second law. However, Maxwell missed something in his analysis.

C. Szilard Engine

The Szilard Engine was proposed by Leo Szilard in 1929. Szilard engine is a cylinder with an ideal gas particle inside. There is a movable partition that can separate the cylinder into the left and right chamber. Two movable pistons are on both ends of the cylinder (Fig. 3a). Szilard used a memory and feedback process to replace the demon in Maxwell's thought experiment. The memory is used to record the position of the gas particle. It has three states: empty, left and right.

In the first step, the movable partition is lowered down to divide the cylinder into left chamber and right chamber. (Fig 3b). The volumes of the two chambers are the same and the probabilities of the gas particle inside either chamber are the same. The second step is the measurement of the position of the gas particle. After identifying which chamber the particle is in, the memory is updated. The third step is the feedback process. The pistons on both ends are moved according to the state of the memory. If the memory is in the right state, the left piston is pushed until it touches the partition (Fig 3d). After that, the partition is moved up so that the gas particle can collide with the piston and move it outward. Some load can be attached to the moving piston and work can be extracted from this process. The heat of the surrounding provides energy to the gas particle to do the work (Fig 3e - 3g). The last step is to erase the memory so that the engine can go back to the initial state.

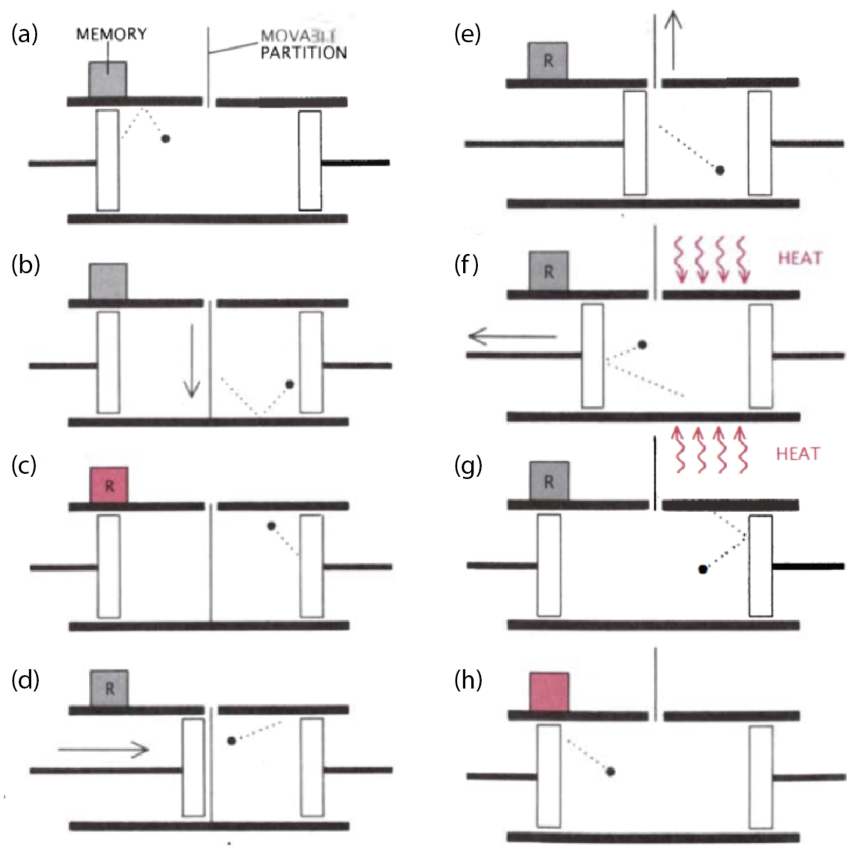

Figure 3: Pictures showing the steps in each cycle of the Szilard Engine [2].

The work done in each cycle can be calculated using the following two equations.

$$PV = Nk_BT$$
$$W = -\int_{V/2}^{V} PdV = -k_BTln2$$

The first equation is the ideal gas law. P is the pressure, V is the volume, N is the number of particles (N = 1 in Szilard Engine) and T is the temperature. Put the first equation into the second equation and the work done W is $-k_BTln2$.

The first law of thermodynamics states that $\Delta U = Q - W$, where ΔU is the change of internal energy, Q is the heat and W is the work done. As the system returns to the same state after each cycle, $\Delta U = 0$ and thus $Q = W = -k_B T \ln 2$. The change of entropy of the engine ΔS_{engine} is thus equal to $Q/T = -k_B \ln 2$. This still violates the second law of thermodynamics because $\Delta S < 0$. Szilard suggested that in order to prevent violation of the second law, some steps in the cycle might generate entropy so that $\Delta S_{total} = \Delta S_{total} + \Delta S_{something} = 0$. He argued that the measurement process created some entropy.

C. Landauer's Principle

Instead of the measurement process, Charles H. Bennett [Bennett, Charles H. "Demons, Engines and the Second Law." *Scientific American*, vol. 257, no. 5, 1987, pp. 108–17] argued that the step responsible for entropy creation is the erasure of memory, not the measurement step. Bennett applied Landauer's Principle to explain Maxwell's Demon. The principle was proposed by Rolf Landauer in 1961 [3]. According to the principle, for all logically irreversible processes, there's a thermodynamic cost. In particular, the erasure of a bit dissipates at least $k_B T \ln 2$ amount of heat to the surrounding.

Logically irreversible processes you cannot deduce the input of the process from just the output of the process only. For example, the output of an AND gate can be 0 and 1. Three combinations of input give 0 as output and only one combination of input gives 1 as output. If the output is equal to 0, it is impossible to deduce whether the input is (0, 0), (0, 1) or (1, 0). Some information loses and cannot be recovered after the process. The memory of the Szilard engine has to be realized by some physical system. Capacitor can be used as the memory because the left state can be represented as a charged capacitor and the right state can be represented as a discharged capacitor. Before the erasure of the memory, the capacitor can be charged or uncharged. However, after the erasure, the capacitor can only have one state only. This is a logically irreversible process and also physically irreversible. $Q = k_B T \ln 2$ dissipates to the surrounding after a bit is erased.

D. Experimental realization of the Szilard Engine

<u>a) Using an optical trap potential to run Szilard Engine</u>
In this paper [4], Tushar et. al put a heavy colloidal particle inside an harmonic potential created by an optical trap. The thermal fluctuation displaces the particle from the equilibrium position. If the particle reaches a threshold position (X_T), the optical potential will raise up so that the equilibrium position of the potential will shift up. As a result, the gravitational energy of the system increases.

The group studied the effect of the sampling frequency, threshold position X_T and bead sizes on the stored power and directed velocity of the Szilard engine. They found that the best values achieved for power and velocity are 1,066 $k_B T$/s and 190μm/s. However, the operational cost of the engine is much larger than the extracted work from the engine.

b) Using a single-electron box to run Szilard Engine

In the paper [5], Koski et. al used a single-electron box (SEB) to run the Szilard engine. The box consists of two small metallic islands connected by a tunnel junction . The electrodes of the box contain a large number of electrons, but by changing the gate potential (V_g) of the electrodes, one extra electron is found on one of the islands (Fig. 4a). The potential on both islands are the same so the extra electron is equally likely on both islands.

Increasing the gate voltage will raise one side of the potential (Fig. 4b), and this decreases the tunneling probability and the extra electron is locked at one of the islands. This step is like inserting a partition in the middle of the Szilard engine cylinder. The location of the extra electron can be detected by a single electron transistor electrometer. If the electron is on the side with lower potential, as V_g is slowly driven back to the original gate potential, the tunneling probability increases. If the electron goes through the potential wall and reaches the side with higher potential, the electron gains energy and work can be extracted from it (Fig. 4c). At the end, the system returns to its original state for the next cycle.

The group found that 0.75 $k_B T$ ln2 of heat can be extracted in each cycle.

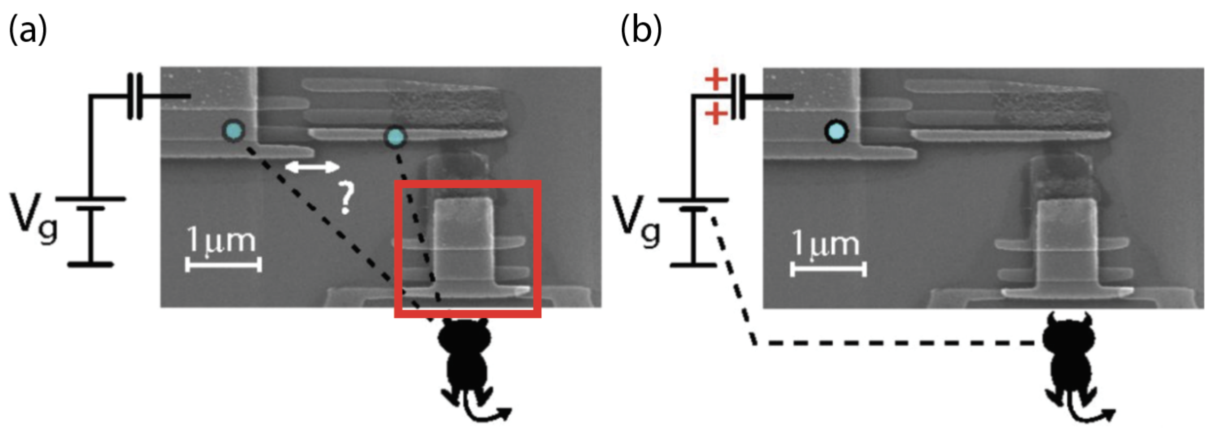

Figure 4: (a) The extra electron (green dots) is equally likely on either metal islands. The component enclosed by the red box is a SET electrometer. (b) Increasing the gate voltage will trap the extra electron in one of the island.

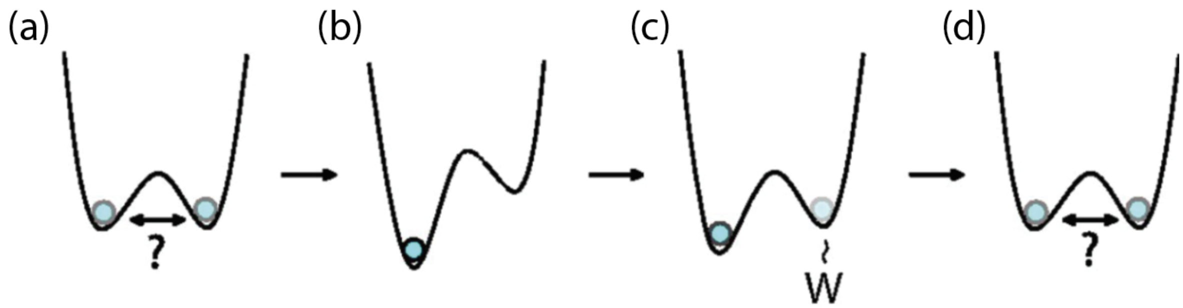

Figure 5: The potential of the two metal islands. (a) In the beginning, the gate voltage is set so that the electron has the same probability to be in either island. (b) Increasing the gate voltage will decrease the tunneling probability and the electron is trapped in one side of the potential well. (c) The gate voltage gradually returns to the original gate voltage. When the electron goes from the low potential side to high potential side, it extracts heat from the surrounding. (d) The system returns to its original state.

E. Conclusion

In this paper, we studied Maxwell's Demon, the Szilard engine and Landauer's principle. We also discussed some experimental realization of the Szilard engine. Two experimental realizations of the Szilard engine are discussed. These two realizations are different from the traditional Szilard engine, which use ideal gas particle as the working substance of the engine. Even though the demon can control and monitor each individual gas molecule, the demon still needs to follow the second law of thermodynamics. In the current stage, the efficiency of the information engine is low and there is still a long way to go to build a useful and efficient information engine.

Bibliography

1. Pal, P.S., Jayannavar, A.M. Maxwell's Demon, Szilard Engine and Landauer Principle. Reson 26, 443–462 (2021).

2. Bennett, Charles H. "Demons, Engines and the Second Law." *Scientific American*, vol. 257, no. 5, 1987, pp. 108–17. *JSTOR*, http://www.jstor.org/stable/24979551. Accessed 9 Jun. 2022.

3. Bennett, Charles H. and Rolf Landauer. "The Fundamental Physical Limits of Computation." Scientific American 253 (1985): 48-56.

4. Saha TK, Lucero JNE, Ehrich J, Sivak DA, Bechhoefer J. Maximizing power and velocity of an information engine. Proceedings of the National Academy of Sciences of the United States of America. 2021 May.

5. Koski, Jonne V., et al. "Experimental realization of a Szilard engine with a single electron." Proceedings of the National Academy of Sciences 111.38 (2014): 13786-13789.