Quantum Heat Engines Driven by Information as Fuel

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September 2016

What role does information play in physics? This is a question that physicists have been discussing for over a decade. It turns out that—by utilizing information as fuel—it is possible to create a heat engine driven with only a single heat reservoir, which originally was thought to violate the second law of thermodynamics. In this thesis, different aspects of a quantum version of such an information heat engine has been studied.

In 1867 James Clerk Maxwell proposed a gedankenexperiment now famously known as Maxwell's demon. This demon was thought of as a tiny intelligent being with the ability to distinguish between individual molecules in a gas so that it could sort them by their velocities and thus create a temperature difference in this gas—since temperature is just a measure of the average energy of the particles in a gas. On first glance, this thought-experiment violates the second law of thermodynamics, the law that prevents us from creating a heat engine that can take energy in form of heat and transform it entirely into mechanical work. If this was possible, an engine could be constructed such that it could do useful work simply by lowering the temperature around us!

By using Maxwell's ideas, Leo Szilard proposed in 1929 a heat engine utilizing only a single heat reservoir. This engine—known as the Szilard engine—could function through the intervention of a Maxwell's demon, extracting work from a single heat reservoir in conflict with the second law of thermodynamics. How a Szilard engine with a single particle works is showed in figure 1.

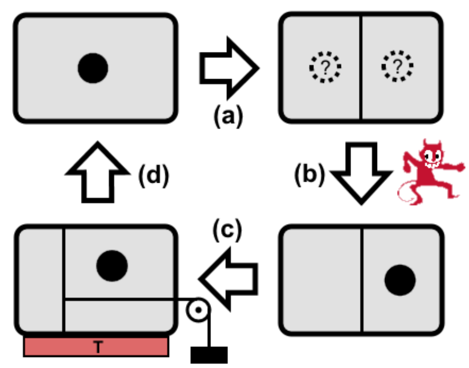

Figure 1: Sketch of the cycle of a Szilard engine with a single particle. **(a)** A separating wall is inserted in the middle of a box with one particle so that this particle is found on either side of the wall with equal probabilities. **(b)** Maxwell's demon intervenes and stores the information about the particle's position. **(c)** Based on the measurement outcome of the demon, an external load can be attached and work can be extracted through an expansion process. **(d)** The engine is reset to its original state.

In the decades following Szilard's clever idea, it was concluded that this information heat engine actually does not violate the second law, since the information processing performed by Maxwell's demon must come at a cost in such a way that second law remains intact.

In this thesis, I have studied a quantum version of Szilard's engine. From earlier analyses, it is known that classical versions of the Szilard engine most likely are of no practical use since the amount of work we can extract from it is very low. By bringing it into the quantum realm—which is needed to describe, for instance, small systems at the nanoscale—we hope to be able to improve this work output as much as possible.

The focus of my study has been on mainly three aspects of this quantum Szilard engine:

- What happens when the particles acting as a working medium of the engine interact with each other?
- How do irregularities or perturbations in the engine affect its behaviour?
- In what way does the engine depend on the speed it is driven by?

My studies of the subject have been mainly numerical, using computers to perform calculations that are not feasible to do by hand.

In previous studies of the quantum Szilard engine, it has been found that a quantum version of this engine can outperform its classical counterpart when the particles used as working medium of the engine do not interact. In this thesis it is found that when the particles are of a special type called bosons, and feel an attractive interaction between themselves, the work output of the engine can be further improved. Due to numerical constraints, only systems consisting of two and three particles have been treated in this thesis. It was, however, found that a system with three particles can outperform a system with two particles in the best-case scenarios, suggesting that perhaps the work output of the engine improves as the amount of particles increases. If this is the case, it is possible that this engine may have practical uses in the rapidly progressing field of nanotechnology.

Additionally, it was found that impurities in the engine can have a large impact on its behaviour. A quantum version of the Szilard engine has not been achieved experimentally, but such an attempt would have to be careful with disturbances in the equipment according to these results.

Finally, it was demonstrated in this thesis that the speed that the engine is driven by can have many unwanted effects. For example, due to the engine being information-driven, the engine may not be able to function at all if driven to quickly. Since it is often desirable to have an engine work quickly so that it can produce a high power, these results highlight a possible problem for this type of engine.