Will state-of-the-art thermodynamics make computers more efficient?

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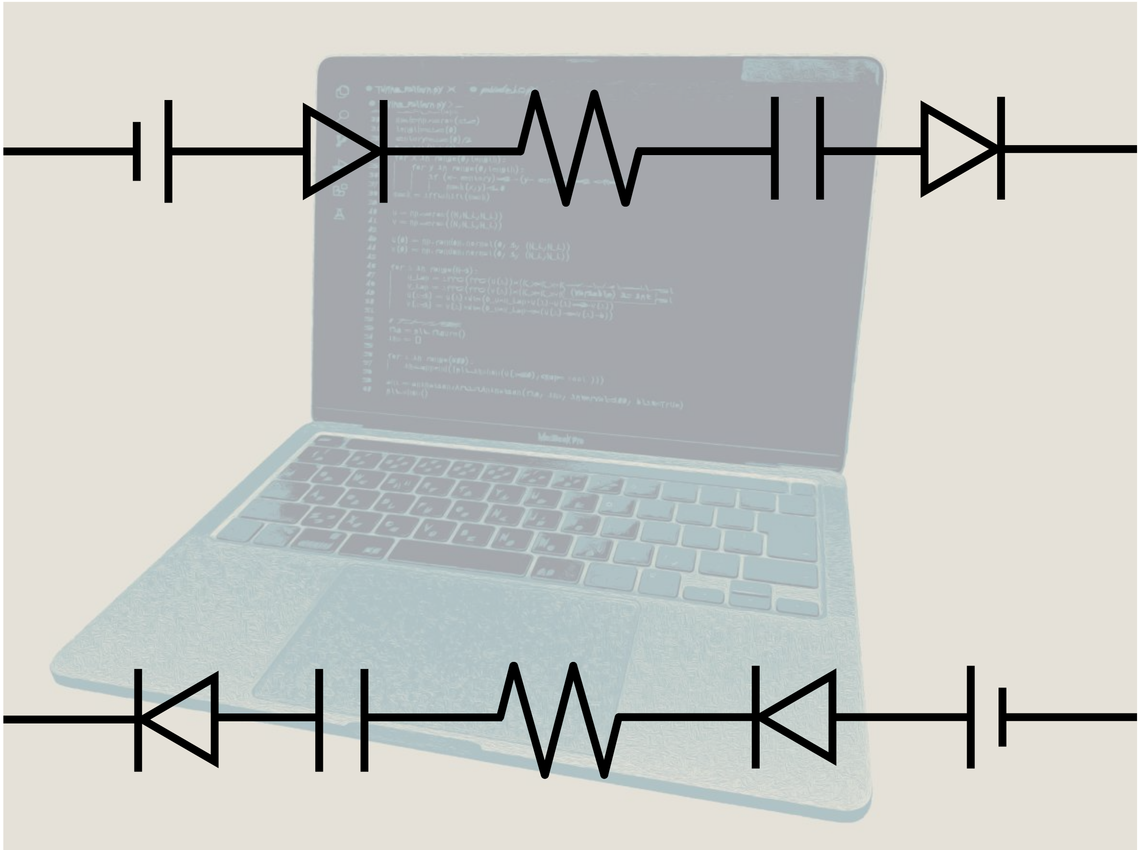

This essay will present research on constructing a way to treat electric circuits using stochastic thermodynamics [1].

Firstly, I will explain this research field. Thermodynamics is an essential field of physics, and most people learn it in school. It is the theory of the equilibrium state: a state reached when we place an object at a specific temperature. In equilibrium, the state of the object does not change. On the other hand, various interesting phenomena occur in states that are not in equilibrium, i.e., non-equilibrium. States involving exciting changes, such as the formation of patterns on the body surfaces of living things, the progression of a chemical reaction, or an electrical circuit in which an electric current is flowing, are all classified as nonequilibrium states. Research on non-equilibrium states is being conducted in various directions because we still do not fully understand non-equilibrium states.

Stochastic thermodynamics is a field that uses probability to study phenomena that occur in non-equilibrium states. Although this field may not be well-known because it is a new field in physics, it is helpful in various fields, such as understanding phenomena that occur in living cells and studying chemical reactions.

A critical factor in this field is fluctuation. Various quantities take on constant values in equilibrium, but this is not always the case in non-equilibrium conditions. The quantity we want to measure is not a constant value but may take many different values. In other words, physical quantities have variance. The variance or standard deviation (or higher order cumulants) of a measured quantity is called a fluctuation.

Let's go back to electrical circuits. Although current and voltage typically follow Ohm's law, the current value can fluctuate due to thermal noise, for example, when the voltage is small enough. The research discussed in this article has established the thermodynamic framework of electric circuits under conditions in which the currents can fluctuate. They discovered that stochastic thermodynamics can explain electric circuits in fluctuating conditions. More specifically, they formulated the behavior of electric circuits using thermodynamic quantities such as heat, fluctuation, and entropy by considering the time evolution of the probability distribution for the number of charges on the conductors that make up the electric circuits.

Building stochastic thermodynamics of electric circuits is very important from two perspectives.

Firstly, we can use this study to consider the efficiency of electric circuits because there is a deep relationship between thermodynamics and efficiency. Thermodynamics historically helped to design the most efficient heat engine feasible. The second law of thermodynamics is one of the most important results, which shows the limit of efficiency. Researchers have studied many other limitations and trade-off relationships in stochastic thermodynamics. For example, the maximum efficiency of a heat engine operating within a fixed time is one of the most important results of this field, which we cannot calculate by ordinary thermodynamics. Constructing stochastic thermodynamics on electric circuits can make it possible to calculate the efficiency and limits of electric circuits using various results that have been studied in the world of thermodynamics.

Secondly, this research will also develop thermodynamics itself. The existing results in stochastic thermodynamics can be calculated in the world of electric circuits using voltages and currents by applying the framework constructed in this study. Researchers in stochastic thermodynamics have often confirmed their results using numerical calculations or small molecules. This study provides the researchers with new options. Now, they can ensure the results of general calculations using electric circuits experimentally. That would contribute to the development of the entire field.

Of course, researchers are not the only ones who will benefit from this research. Understanding the characteristics and efficiency of electric circuits under fluctuating currents will lead to industrial applications. For example, we could apply this research to make classical computers more efficient. This application is bound to have an impact on society.

Today, the performance of classical computers is one of the most critical issues. Quantum computers have been a hot topic recently, but they are not necessarily more helpful than classical computers in all situations. Thus, we will continue to use classical computers even if quantum computers are put to practical use. Therefore, various efforts are underway to improve classical computers. As a result, the computational power and the storage capacity of computers are only increasing.

In contrast, the efficiencies described here do not simply increase the computer's power. Instead, the idea is to make computers run on less energy. We can regard that this research deals with a situation where the voltage is small, and the current behaves unstable by being exposed to thermal noise. The electronic devices we use in our daily lives stably behave because we apply sufficient voltage to them. In other words, reducing the voltage applied will also fluctuate the current flowing through these electronic devices, which is the subject of this study. The computers are no exception. We can regard them as huge-scale electric circuits. So, we may be able to use the results of this research to calculate the magnitude of voltage required for a computer to operate well. Alternatively, we may be able to design new computers that operate accurately at smaller voltages.

If we can invent electronics that operate at smaller voltages, it will save energy. We are paying a tremendous cost to produce energy. For example, we affect the environment through thermal power generation. If we only continue to increase the power of computers, the energy requirements will increase and, consequently, the cost we must pay will increase. However, if we make computers more efficient to operate at lower voltages, the energy requirements will decrease, and this problem will be alleviated. Although the research presented here is highly theoretical, it has the potential to help with solving a global energy problem.

Reference

[1] Freitas, N., Delvenne, J. C., & Esposito, M. (2021). Stochastic Thermodynamics of Nonlinear Electronic Circuits: A Realistic Framework for Computing Around kT. Physical Review X, 11(3), 031064.