Quantum knowledge cools computers: New understanding of entropy

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From a laptop warming a knee to a supercomputer heating a room, the idea that computers generate heat is familiar to everyone. But theoretical physicists have discovered something astonishing: not only do computational processes sometimes generate no heat, under certain conditions they can even have a cooling effect. Behind this finding are fundamental considerations relating to knowledge and a lack of knowledge. The researchers publish their findings today in the journal *Nature*.

When computers compute, the energy they consume eventually ends up as heat. This isn't all due to the engineering of the computer – physics has something to say about the fundamental energy cost of processing information.

Recent research by a team of physicists reveals a surprise at this fundamental level. ETH-Professor Renato Renner, and Vlatko Vedral of the Centre for Quantum Technologies at the National University of Singapore and the University of Oxford, UK, and their colleagues describe in the scientific journal Nature how the deletion of data, under certain conditions, can create a cooling effect instead of generating heat. The cooling effect appears when the strange quantum phenomenon of entanglement is invoked. Ultimately, it may be possible to harness this effect to cool supercomputers that have their performance held back by heat generation. «Achieving the control at the quantum level that would be required to implement this in supercomputers is a huge technological challenge, but it may not be impossible. We have seen enormous progress is quantum technologies over the past 20 years,» says Vedral. With the technology in quantum physics labs today, it should be possible to do a proof of principle experiment on a few bits of data.

Landauer's principle is given a quantum twist

The physicist Rolf Landauer calculated back in 1961 that during the deletion of data, some release of energy in the form of heat is unavoidable. Landauer's principle implies that when a certain number of arithmetical operations per second have been exceeded, the computer will produce so much heat that the heat is impossible to dissipate. In supercomputers today other sources of heat are more significant, but Renner thinks that the critical threshold where Landauer's erasure heat becomes important may be reached within the next 10 to 20 years. The heat emission from the deletion of a ten terabyte hard-drive amounts in principle to less than a millionth of a joule. However, if such a deletion process were repeated many times per second then the heat would accumulate correspondingly.

The new study revisits Landauer's principle for cases when the values of the bits to be deleted may be known. When the memory content is known, it should be possible to delete the bits in such a manner that it is theoretically possible to re-create them. It has previously been shown that such reversible deletion would generate no heat. In the new paper, the researchers go a step further. They show that when the bits to be deleted are quantum-mechanically entangled with the state of an observer, then the observer could even withdraw heat from the system while deleting the bits. Entanglement links the observer's state to that of the computer in such a way that they know more about the memory than is possible in classical physics.

Similar formulas – two disciplines

In order to reach this result, the scientists combined ideas from information theory and thermodynamics about a concept known as entropy. Entropy appears differently in these two disciplines, which are, to a large extent, independent of each other. In information theory, entropy is a measurement of the information density. It describes, for instance, how much memory capacity a given set of data would take up when compressed optimally. In thermodynamics, on the other hand, entropy relates to the disorder in systems, for example to the arrangement of molecules in a gas. In thermodynamics, adding entropy to a system is usually equivalent to adding energy as heat.

The ETH physicist Renner says «We have now shown that in both cases, the term entropy is actually describing the same thing even in the quantum mechanical regime». As the formulas for the two entropies look the same, it had already been assumed that there was a connection between them. «Our study shows that in both cases, entropy is considered to be a type of lack of knowledge», says Renner. The new paper in Nature builds on work published earlier in the *New Journal of Physics*.

In measuring entropy, one should bear in mind that an object does not have a certain amount of entropy per se, instead an object's entropy is always dependent on the observer. Applied to the example of deleting data, this means that if two individuals delete data in a memory and one has more knowledge of this data, she perceives the memory to have lower entropy and can then delete the memory using less energy. Entropy in quantum physics has the unusual property of sometimes being negative when calculated from the information theory point of view. Perfect classical knowledge of a system means the observer perceives it to have zero entropy. This corresponds to the memory of the observer and that of the system being perfectly correlated, as much as allowed in classical physics. Entanglement gives the observer „more than complete knowledge" because quantum correlations are stronger than classical correlations. This leads to an entropy less than zero. Until now, theoretical physicists had used this negative entropy in calculations without understanding what it might mean in thermodynamic terms or experimentally.

No heat, even a cooling effect

In the case of perfect classical knowledge of a computer memory (zero entropy), deletion of the data requires in theory no energy at all. The researchers prove that "more than complete knowledge" from quantum entanglement with the memory (negative entropy) leads to deletion of the data being accompanied by removal of heat from the computer and its release as usable energy. This is the physical meaning of negative entropy.

Renner emphasizes, however, "This doesn't mean that we can develop a perpetual motion machine". The data can only be deleted once, so there is no possibility to continue to generate energy. The process also destroys the entanglement, and it would take an input of energy to reset the system to its starting state. The equations are consistent with what's known as the second law of thermodynamics: the idea that the entropy of the universe can never decrease. Vedral says "We're working on the edge of the second law. If you go any further, you will break it."

Fundamental findings

The scientists' new findings relating to entropy in thermodynamics and information theory may have usefulness beyond calculating the heat production of computers. For example, methods developed within information theory to handle entropy could lead to innovations in thermodynamics. The connection made between the two concepts of entropy is fundamental.

More information: Del Rio L, Aberg J, Renner R, Dahlsten O & Vedral V: The thermodynamic meaning of negative entropy, *Nature* (2011) DOI:10.1038/nature10123

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