MONEY FOR NOTHING

Can quantum effects overcome the limits imposed by the laws of thermodynamics?

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Word count: 2341

Illustration of demon taken from Jacques Collin de Plancy's *Dictionnaire Infernal*. Available on Wikimedia commons, at https://commons.wikimedia.org/wiki/File:Deumus.png

Any great technological revolution brings with it not only an increase in productivity, but also a newfound understanding of the limits of our attainment. At the dawn of the information age this was Turing's realisation that there are tasks classical computers simply cannot perform (Turing, 1938); during the industrial revolution this was Lord Kelvin and Rudolf Clausius's independent formulations that perpetual motion machines of the second kind (those that extract heat from their surroundings and efficiently turn it into work) are impossible to construct (Redding, 1969). This would later be shown to be equivalent to the 2nd law of thermodynamics as we understand it today: that any process brings with it an increase in entropy. However, whereas Turing's thesis was based on pure mathematics, the 2nd law is entirely empirical, which, to some, suggests that it might not be as strict as Kelvin and Clausius assumed.

A defence of the 2nd law usually takes its basis in the statistics of many-body dynamics, which can be intuited by considering billiard balls on a table following a break. With 15 balls on a table of a few square metres, the possible arrangements over the felt are unimaginably large. If one was to try and strike the balls so that they returned to their original, ordered formation – equivalent to reducing the system's entropy – the strike would have to be so incredibly precise it would be effectively impossible. However, consider just two balls, and suddenly the simplicity of the system means that an attempt to reduce the system's entropy becomes a real possibility: accurately manipulating the paths of two balls is what we do every time we play billiards! By this line of thought, some sliver of hope of overcoming the 2nd law is offered in the consideration of simple enough systems, or ones that an agent can understand and influence precisely enough. In his 1871 *Theory of Heat* Maxwell posited that the 2nd law was only the result of statistics and our inability to quantify systems accurately. He imagined a 'demon' residing over a system, which, by being sufficiently capable of accurate observation and influence, could reduce the system's entropy (Maxwell, 1871). Maxwell imagined a box partitioned into two equal volumes, initially at thermal equilibrium (see Figure 1, below). By controlling a door in the partition so that any fast-moving particles were only allowed to travel left, while slow ones only right, the average kinetic energy on each side could be manipulated without any entropy increase. This would directly violate Clausius' formulation of the 2nd law.

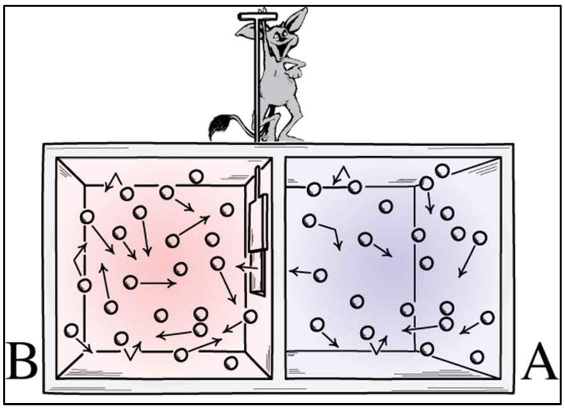

Figure 1: Maxwell's demon illustration, taken from John Norton of University of Pittsburgh (Norton, 2013)*. As later shown, the entropy does increase, despite the demon's best efforts, but outside the box, in the demon's brain.*

Later, with the advent of information theory, it was shown that Maxwell's demon failed to reduce the entropy of the whole system if the demon was included in that picture. Any calculation process, but specifically those involving reading and writing to and from memory (Maruyama, Nori and Vedral, 2009) must involve an entropy increase, which can be shown to outweigh the entropy decrease corresponding to any decision to open or close the partition door.

Subsequent attempts to build devices that manipulate the entropy and other thermodynamic properties of systems on microscales have consequently been coined 'Maxwell's demons'. Some hope remains that, by considering and leveraging specific effects on the quantum level, we can begin to envision new ways to extract work from heat without increasing entropy, because we can control every aspect of the system sufficiently accurately and precisely. Often, this takes the form of creating 'autonomous' demons, which work based on simple physical processes, rather than ones based on the decision making of some agent (Ptaszyński, 2018).

Recently, a major line of attack into finding a working Maxwell's demon has involved research into the overlap between the fields of spintronics and quantum thermodynamics (Katcko *et al.*, 2019), and it is the device that Katcko created earlier this year that provides an intriguing insight into the possibility of creating a working demon.

Light and Heat

In a sentence, Katcko's device is – as he points out – to thermal energy as the solar cell is to light (Katcko *et al.*, 2019). Photovoltaic cells are carefully constructed so that incident photons displace electrons, causing them to have a net drift velocity round a circuit, while the positively charged holes they leave behind drift in the opposite direction, creating a current that can be harnessed to do useful work.

Recent advancements in magneto-electronics (Hai *et al.*, 2009) and spin-filter tunnelling (Moodera, Santos and Nagahama, 2007) have allowed the construction of comparable potential landscapes in magnetic materials that generate current as a result of background thermal energy, rather than incident solar energy.

At any non-zero temperature, we expect the microstate properties of a system to be in some probabilistic distribution, and, even at equilibrium, for those properties to be constantly fluctuating about some mean. As a result, on the paramagnetic central sheet at the core of Katcko's device, the spins of the electrons present are always changing and flipping, from an up (↑) state to a down (↓). It is these ongoing thermal fluctuations that Katcko uses to generate work in the device (Katcko *et al.*, 2019).

However, random variations alone are not enough to generate power: some clever mechanics is needed to turn the aleatoric motion into something predictable and useful. This comes in the form of two ferromagnetic electrodes in contact with either side of the central sheet, which operate as spintronic selectors (Miao *et al.*, 2014): that is, they only facilitate electron exchange with one spin orientation. For example, ↑ electrons can only transfer left, while ↓ electrons can only transfer right. Assuming a 50:50 distribution of ↑:↓ electrons, this would result in a net current of 0, because the same number of charged particles would be travelling in each direction. However, by achieving a spin-polarisation of the device, and therefore biasing the ratio of spins away from unity, a net current can be achieved (see Figure 2, below).

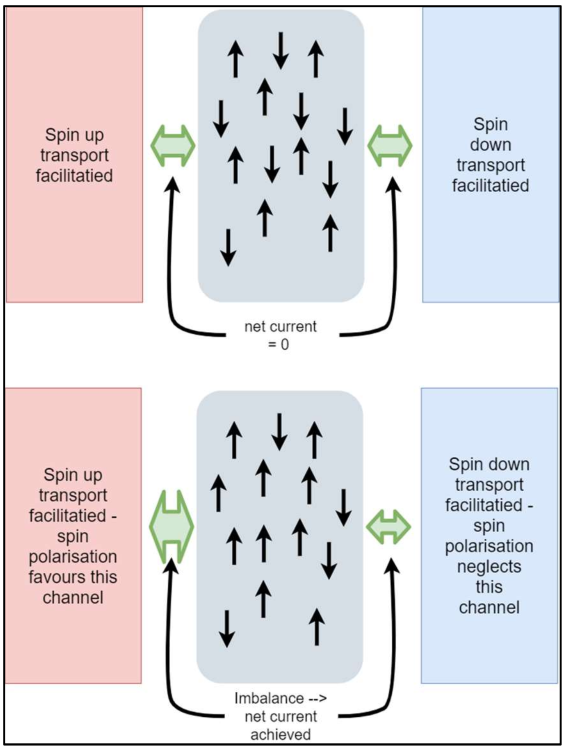

Figure 2: Schematics of Katcko's device to show electron spin-based exchange as spin polarisation is switched off (top) or on (bottom), to achieve a net current across the device. Adapted and simplified from (Katcko et al., 2019).

Although the spin polarisation can be achieved in a number of ways, Miao and Katcko both use the ferromagnetic properties of rare-earth ions to control the orientation of the conduction electrons on the paramagnetic centre. This works by shifting the relative energy levels of the two spins away from equality, so one would be favoured over the other. Consequently, a net spin imbalance can be achieved, and a resultant current observed. This led to a room-temperature power generation of over 1 nW.

As Katcko points out, this technology is incredibly exciting for a number of practical reasons. As a chip-based power source that can operate in isolation of any external input except background temperature, there are numerous applications in 'always-on' technologies like pace-makers or computers in extreme environments. Moreover, the power density achieved by Katcko's device exceeds the raw solar power density on Earth by a factor of 300 (Katcko *et al.*, 2019), meaning that in the future it may play a role in renewable energy production.

However, perhaps more intriguing are the thermodynamic implications of the device. Not only does the device do useful work in generating an electrical current, but because it is powered by thermal energy it also cools the device, something that would usually require and input of useful work, not the other way around. Therefore, the device initially seems to work as an effective Maxwell's demon, reducing the entropy of its surroundings whilst also producing a useable current.

Beyond the demon

Although several solutions to 'exorcise' Maxwell's demon exist, the most common attribute the entropy increase to a system coupled to the one the demon acts on (Maruyama, Nori and Vedral, 2009), for example by increasing the entropy of computer memory, if the demon is digital in nature. Similarly, in the case presented above, it is necessary to consider the systems coupled to the device, and not just the device itself.

To this end, the thought experiment of Mandal and Jarzynski provides a useful analogy (Mandal and Jarzynski, 2012), and is illustrated below in Figure 3. Here, a demon is imagined to work by rotating a wheel entirely at the behest of thermal fluctuations, so at

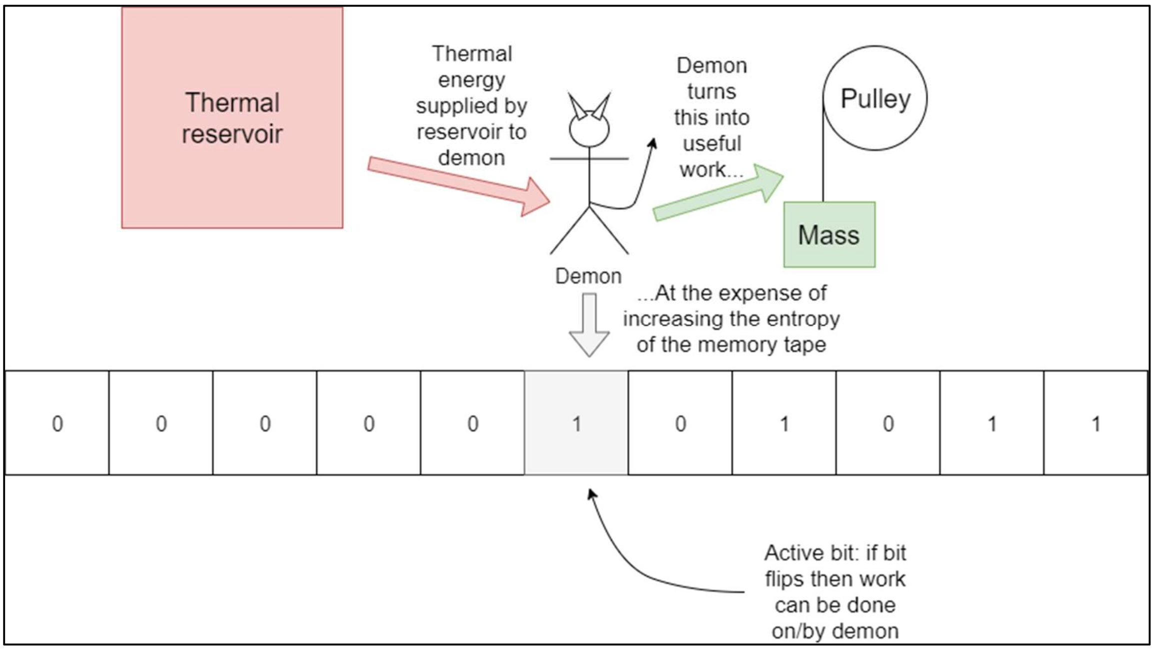

Figure 3: Schematic simplification of Mandal and Jarzynski's thought experiment demon, adapted and simplified from (Mandal and Jarzynski, 2012).

any given moment it might spin a little to the left or right. This wheel is coupled to two systems: the first, a weight on a pulley in a gravitational field, which provides an output for the system's useful work, and secondly, a reel of Turing machine-style memory tape, which can either hold a value of 0 or 1 for any point on the tape. Every time the wheel makes a full turn clockwise, the current bit of the tape is set to a 1, and the weight is raised provided that the bit at that memory location has swapped from a 0 to a 1. For an anti-clockwise rotation, the opposite behaviour is observed. As a result, the machine operates as so:

1. Provided the incoming memory tape is all blank 0s, then any full clockwise turn will raise the weight. Any counter-clockwise turn will set the current bit to a 0, but because no bit-flip has occurred, the weight doesn't change height. As a result, the input of a low-entropy memory provides the capacity for the demon to do work, at the expense of increasing the entropy of that memory by $k_B\ln(2)$ every time the weight is raised.
2. Conversely, should the incoming memory be a messy mixture of 0s and 1s, then the demon finds itself incapable of doing work: in fact, on average, the mass drops a short distance per bit. However, this comes at the benefit of wiping the memory, something that must require work to perform as per Landauer's Principle (Plenio and Vitelli, 2001).

The secret lives of ferromagnets

Returning to Katcko's device, we draw up the analogy as follows: the demon becomes the paramagnetic centre and attached spintronic selectors, while the pulley and weight become the useful current we can extract. The memory tape represents the domains in the ferromagnets used to induce the spin polarisation across the paramagnetic centre: provided these are in a low entropy state (like the blank tape) then they will provide a strong magnetic field and therefore effectively polarise the spins so essential to the device. As a result, in the same way that the memory in Mandal's experiment is written to, and consequently increases in entropy, we expect to see a similar increase in the entropy of the ferromagnets, such that their domains fall out of alignment. This renders them less able to generate a strong field and thus less useful to the device's operation, just like how when Mandal's memory tape arrives disordered, the demon cannot use it to do work.

Although this means that the Katcko's device has not circumvented the 2nd law, it nonetheless remains a fascinating technology. The substantial built-in energy of ferromagnets (Katcko et al., 2019) mean that they have incredible potential as 'spin batteries' (Hai et al., 2009), with a real capacity to develop competitive power outputs.

Similarly, in the same way that Mandal's demon can be used to wipe the memory of the tape at the expense of having useful work done on it, an interesting route of investigation could be into whether Katcko's device, reversed with an external current passed across it, could be used to rectify domain alignment in a ferromagnet.

Similarly, although the analogy to Mandal and Jarzynski's thought experiment provides a useful qualitative analogy, two key questions remain.

First, when they introduce the coupled memory tape into the thought experiment it is an arbitrary addition used to satisfy the 2nd law, meaning the device's inability to operate as a true Maxwell's demon was inevitable. Although inapplicable to that specific example, it would be interesting to remove the tape, and see if a more simplified thought experiment with the means to provide a way round the entropy increase could actually be composed.

Second, it stands that a more quantitative analysis should be possible, wherein the exact entropy change in Katcko's ferromagnets, as well as the effect this would have on the field strength, could be quantified, thus verifying the working of the device in relation to the 2nd law more rigorously. The relationship between ferromagnet domain alignment (Jiles and Atherton, 1984), entropy (Norihiko *et al.*, 2004; Gao *et al.*, 2009) and magnetic field strength is well studied. One line of investigation would be to measure the change in strength of the magnets in Katcko's device, convert this to an entropy increase, and then compare this back to the entropy decrease on the paramagnetic centre due to the fall in temperature and more ordered spin alignment, and consequently see how close to conserving entropy – or even reducing it – the device had come.

Truth, Transgression and Thermodynamics

Curiosity is a defining trait of the human condition, so it is little wonder that we are so obsessed with pushing the boundaries of what we believe to be possible. Although Katcko's device fails to operate as an effective Maxwell's demon, it nonetheless stands as an excellent example of how academic research to explore the limits of physical possibility can have ground-breaking real-world applications.

If the immutability of the 2nd law is due to something more than simple statistics, as the continued failure to produce a working Maxwell's demon suggests, then perhaps it is based on something more fundamental in our universe, linked simply to the passage of time as all things tend to chaos. However, failure to produce a demon, no matter how many times, does not constitute a proof that it is impossible, offering some hope that, as physics becomes increasingly well understood, we may be able to push the boundaries of what is possible once again.

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