Photonic Maxwell's Demon: Feed-forward methods for photonic thermodynamic tasks

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Abstract. Maxwell's Demon is at the heart of the interrelation between quantum information processing and thermodynamics. In this thought experiment, a demon extracts work from two thermal baths at equilibrium by gaining information about them at the single-particle level and applying classical feed-forward operations. In this talk I will show how to implement a photonic version of Maxwell's Demon with active feed-forward in a fiber-based system using ultrafast optical switches. This is the first realisation of an active Demon. The experiment [1] shows that, if correlations exist between the two thermal baths, the Demon can extract over an order of magnitude more work than without correlations. This demonstrates the great potential of photonic experiments – which provide a unique degree of control on the system – to access new regimes in quantum thermodynamics.

1 Maxwell's demon as feed-forward

Thermodynamics was conceived as a phenomenological theory for the equilibrium properties of macroscopic systems ranging from gas (ensembles of 'many' small systems) to black holes, of which the theory provides a complete description in terms of quantities like temperature or work. On the other hand, the manipulation of thermal states (as well as their emergence from fluctuations at the smallest scale) is described in terms of (quantum) information processing. This interrelation is perhaps best manifested in the protocol known as 'Maxwell's demon' (MD): As illustrated in Fig. 1 **(a)**, the MD monitors the motion of gas particles inside a partitioned box. Based on its previous knowledge of the particle's temperature, the MD can sort hot particles from cold particles by opening an aperture in the partition such that all hot particles eventually end up on one side of the partition and all cold particles on the other. So the MD brings the system out of equilibrium, and can exploit the engineered temperature differential to extract work without violating the second principle of thermodynamics. In other words, the MD generates work by measuring individual particles to gain information, and depending on these measurement results, it applies different operations to the bath (i.e. opening the door, or leaving it closed). These measurement-dependent operations are called feed-forward operations.

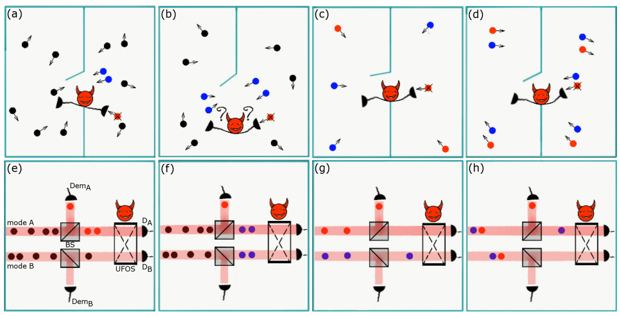

Figure 1. Principle of operation of the photonic Maxwell's Demon (MD): the MD controls the path of particles/photons in the system. The colours red and blue represent correlated photons; i.e. when the demon measures a red particle, it learns the location of the blue particle. Top row, particle picture of the photonic MD; bottom row, actual implementation of the photonic MD. **(a)** and **(e)**, uncorrelated thermal states; **(b)** and **(f)**, split thermal states; **(c)** and **(g)** correlated states; **(d)** and **(h)**, anti-correlated states. Figure from [3].

2 Photonic implementation

The 'power' of the MD, the amount of work it can extract per measurement, can be greatly enhanced by operating with correlated particles: Consider a situation where, for every particle moving in a certain direction in the left bath, there is a twin particle moving in the same direction in the right bath, as illustrated in Fig. 1 **(c)**. If the MD observes a particle in the left bath it also learns something about an (unobserved) particle in the right bath. Because of this ad-

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ditional information, the MD can extract much more work per measurement [2] by simply modifying its feed-forward protocol to make use of the new information.

In a photonic MD, the baths are realised with optical modes [3], each containing a thermal state of photons whose average photon number directly sets the temperature of the bath. These two optical modes are then sent to individual detectors, D_A and D_B. When the two optical modes have an equal photon number (the baths have an equal temperature), the detectors register the same counts and no work can be extracted. When a photon is subtracted from this state at a beamsplitter and detected in the reflection port with detector Dem_A or Dem_B, bunching will occur, meaning that the photon number in the transmitted beam will be temporarily doubled (as depicted in red in Fig. 1 (**e**)). This photon extraction provides information about the average photon number in the beam, based on which a classical feed-forward operation may then be applied to create an imbalance in the photon number between the two beams. This energy imbalance can in turn be used to extract work.

3 First active Maxwell's Demon

We have implementd a photonic MD with active feed-forward (more details in [1]) to physically swap the paths of the beams dependent on detection events at Dem_A and Dem_B using an ultra-fast optical switch (methods adapted from [4]). Furthermore, we have used correlations as a resource to increase the power of the MD.

The choice of correlations is essential in enabling the MD to extract work. The experiment [1] evidences that particular correlations allow for an order of magnitude increase of the power of the MD, while others prevent the MD from extracting any work at all. In conclusion, information processing with correlations and anti-correlations vastly outperforms operation with the other states.

References

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