T_H and T_C are kept constant. In small systems, Q_τ is a fluctuating quantity but its average is positive as imposed by the second principle. The fluctuation theorems relate the probability $P(Q_\tau)$ of exchanging the heat quantity Q_τ with $-Q_\tau$ according to:

$$\ln \frac{P(Q_\tau)}{P(-Q_\tau)} = \Delta\beta Q_\tau$$

where $\Delta\beta = (1/T_C - 1/T_H)/k_B$, k_B is the Boltzmann constant and $\Delta\beta Q_\tau$ can be easily identified as the entropy production during time τ (refs 1–3,7). These findings are very important because they use statistical mechanics to answer questions well beyond both the average (that is, thermodynamic case) and the standard fluctuation theory (normally dominated, away from critical points, by the so-called central limit theorem) to look at extremes. Similar relationships can be derived for the work and the entropy as indicated in equation (3) of ref. 4. It is worth noting that the authors use a specific form of entropy: the total entropy S (ref. 1). This entropy contains the standard contribution given by the heat exchanged with the bath and a statistical contribution (Φ), which takes into account the probability of finding the system in a particular position of the phase space. The mean value of Φ is zero in such a way that the mean value of S is determined only by the average heat exchanged with the bath, as it would be in the macroscopic case. Thus Φ is important only for entropy fluctuations.

Fluctuation theorems have already been experimentally tested in several systems such as harmonic oscillators, trapped colloidal Brownian particles, atomic force microscope tips and relaxing colloids[1–3]. The novelty of Novotny and co-workers' work is that it considers the case of a system — nanomechanical oscillator composed of a nanoparticle trapped in vacuum by a laser beam — that is out of equilibrium. Because of the very low viscous dissipation the oscillator is underdamped. The particle is artificially cooled by a feedback system in such a way that it has an effective temperature T_{fb} much smaller than that of the real heat bath. This initial state is not an equilibrium state because it is artificially obtained by the feedback force. On top of the feedback the authors added another external force F_{mod} and drove the system in an even more complex out-of-equilibrium steady state. Starting from one of these two out-of-equilibrium states the authors suddenly switched off all the forces and recorded how the system relaxed towards equilibrium with the heat bath. During the relaxation they measured the entropy production and by repeating the experiment many times they were able to construct the statistics of this quantity and check that the fluctuation theorems were verified in this case. The theoretical analysis is in excellent agreement with the experimental results. These kinds of experiment are useful for a better understanding of the energetic efficiency and of the heat exchanges in nanosystems, for example, a Carnot cycle for nanomotors and the heat transfer between two coupled nanodevices at different temperatures. ❐

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OPTICAL DEVICES

Localizing light with electrons

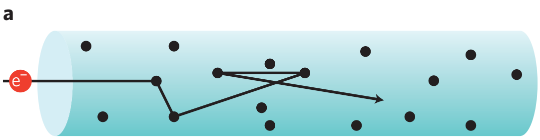
Electronic control of optical Anderson localization can be achieved in optical waveguides with embedded diodes.

Sergey E. Skipetrov

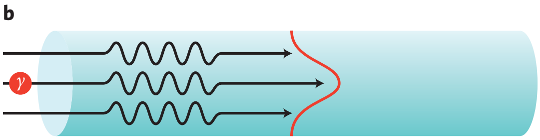
Anderson localization — suppression of wave propagation by disorder — can be observed for both quantum and classical waves[1], and is easy to achieve for electrons in disordered conductors at sufficiently low temperatures[2]. However, observing the effect with light or sound is a significant experimental challenge[3,4]. Control over Anderson localization of light has previously been achieved by exploiting nonlinear optical effects that modify the scattering strength of a sample[5]. Alternatively, Anderson localization is expected to be affected by an external magnetic field that breaks the time-reversal invariance[6]. However, both strong magnetic fields and high laser intensities (which are required for nonlinear optical effects) are unwelcome in technological applications. Writing in *Nature Nanotechnology*, Shayan Mookherjea and colleagues at the University of California, San Diego and the Institute of Microelectronics in Singapore now show that Anderson localization of light can also be controlled electronically[7].

The transport of elementary excitations in electric wires and optical fibres — electrons and photons, respectively — is fundamentally different. At room temperature, electrons propagate in a metallic wire like tiny balls, which bounce off the defects in the crystalline structure of the wire, as well as other impurities (Fig. 1a). This is why electrons, despite the constant electric forces acting on them, do not experience a constant acceleration and instead move at a constant velocity. In other words, the electric force due to an applied voltage is compensated by the friction due to impurities. This leads to the well-known Ohm's law and the resulting dissipation of a considerable amount of energy into heat.

The situation is different in optical fibres, which are designed and fabricated to be extremely pure and homogeneous. Photons will, for example, meet almost no impurities in a kilometre-long fibre, and will propagate ballistically without scattering (Fig. 1b). If optical fibres were as disordered as metallic wires, the propagation of light through them would be blocked completely. This phenomenon is known as Anderson localization of light, which is the result of complicated interferences of multiply scattered waves that are collectively destructive (Fig. 1c). The phenomenon also takes place — and, in fact, was first discovered[2] — for electrons in disordered conductors, but only at very low temperatures when



Electron in a disordered wire



Light in a high-quality optical fibre

Light in a disordered optical fibre

Figure 1 | Three regimes of transport at room temperatures. **a**, Electrons (e^-) in metal wires propagate by diffusion, bouncing from impurities (black dots) as classical particles. **b**, Light (γ) in an optical fibre follows straight, ballistic trajectories. The red line shows the intensity profile typical for light in an optical fibre. **c**, Propagation of light in a disordered fibre is blocked by destructive interferences of waves following various scattering paths.

electrons start to exhibit their wave nature and gain the ability to interfere. Light, on the other hand, exhibits wave properties independent of temperature and may experience Anderson localization even at room temperatures[8].

Disorder is generally detrimental for light transport, but, as Mookherjea and colleagues demonstrate[7], it can also be useful. Their idea is to switch between inhibited (Fig. 1c) and diffusive (Fig. 1a) transport of light (where in Fig. 1a, the electrons would be replaced by photons) by electrically controlling the optical disorder in the sample. To achieve this, they fabricated samples in which each impurity (that is, each black dot in Fig. 1) is an electric diode that changes the phase of scattered light as a function of the voltage applied to the diode. Such a phase change significantly perturbs the subtle interferences leading to the build-up of Anderson localization and the inhibition of transport (Fig. 1c). Deprived of phase coherence, light loses its ability to interfere. The destructive interferences leading to Anderson localization become impossible and light propagation becomes diffusive, similar to the propagation of electrons in a metal wire (Fig. 1a). However, when the voltage on the diodes is turned off, the phase coherence of scattered light is restored and Anderson localization is recovered. In this way, by turning the voltage on and off, the researchers managed to modulate the amount of light transmitted through a disordered waveguide by two orders of magnitude, which is more than sufficient to envisage practical applications.

The results of Mookherjea and colleagues are made possible by an ingenious combination of optical and electronic technologies, created through nanofabrication methods that allow the functional electronic circuits to be fabricated inside each scatterer of light. Using electronics to control light propagation is a compromise between the switching speed (which would be maximal for an all-optical solution) and practical implementation. This compromise allows high laser intensities (which would be required for an all-optical solution) or strong magnetic fields (which could affect Anderson localization as well) to be avoided.

These results are an important step in the design of complex electronically controlled optical circuits. Such circuits could perform information processing tasks or serve as light emitters — random lasers[9] — with new properties and functionalities. The range of possibilities could also be extended if the principle demonstrated by the researchers in a one-dimensional system was extended to higher dimensions. Although going to two dimensions should be possible, building a three-dimensional device may be problematic because the electric wiring of the scatterers (the diodes) could disturb the propagation of light. If, however, such a three-dimensional realization was possible, it could provide a remarkable way of confirming that the deviations from diffusive transport of light observed in experiments[4] are due to the Anderson localization phenomenon. Switching Anderson localization on and off without changing any other property would certainly be the best way of proving this and convincing the skeptics[10]. ❐

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