Directed motion from random noise

Fears that biochemical ratchets as explanations of muscle contraction (among other things) would contradict the Second Law of Thermodynamics have been stilled by an interesting counter-example.

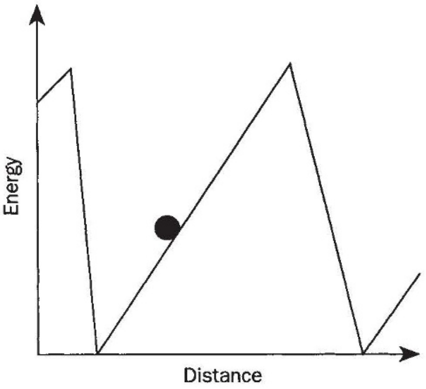
No apologies are required for returning so soon to the question of whether the contraction of muscle fibres, or the transport of macromolecules along microtubules, entails some kind of ratchet mechanism in which molecules are able to move relative to each other in one direction, but are unable to slip backwards (see *Nature* **368**, 287; 1994). For if these processes do involve a biochemical ratchet, that would be important. But there is one snag: in, for example, transport along microtubules, there is no known gradient of chemical concentration or of temperature to determine the direction of the movement. That is another way of saying that the ratchet explanation appears to contradict the Second Law of Thermodynamics, which would be a serious matter.

The point can be illustrated with the help of Maxwell's demon. Suppose that microtubules have a periodic structure extending along their length, and that materials being transported along them are normally bound at sites that are also distributed periodically. If the molecule is to move, it must be given at least enough energy to surmount the energy peak between two minima. But what will ensure that it can move only in one direction? A Maxwellian demon at each binding site instructed to prevent backwards movement could do the trick, but that is merely to confess that the Second Law, which outlaws Maxwell's demon, is violated. Is there a way round the difficulty?

The point is of some historical interest because a model of a mechanical ratchet was used in *The Feynman Lectures in Physics* to show that useful work cannot be extracted from thermally driven fluctuations, or 'white noise'. It is simplest to begin with a strictly mechanical one-dimensional ratchet in which an object (the black sphere in the diagram) can move in one direction only, but in a periodic structure with a periodic potential (of which one sawtooth is displayed). Feynman's question (answered in the negative) was whether the asymmetry of the ratchet structure would determine the movement of the particle in one direction rather than the other under random impacts from, say, the molecules of a perfect gas at some non-zero temperature.

It is not difficult to reach the conclusion that there can be no preferred direction of motion. What matters is whether the particle will acquire enough kinetic energy to surmount the sawtooth, and that is as likely to happen in one direction as the other.

But what if the noise is not white noise? That is the question now taken up by Charles R. Doering, Werner Horsthemke and Jason Riordan (the first and third from Clarkson University, Potsdam, New York, and the second from the Southern Methodist University in Dallas, Texas). Their argument appears in the current issue of *Physical Review Letters* (**72**, 2984–2987; 1994). To simulate the properties of biological structures, they suppose that the motion of the particle in the sawtooth ratchet potential will be over-damped, as in a viscous medium, implying that its motion will be determined by equating its velocity to the sum of all the forces to which it is subjected — the potential gradient and the noise. Feynman's conclusion (that white noise yields no net motion) still applies.



Non-white noise must be defined. In a perfect gas, the motion of different molecules is strictly independent. The chance that an object which is macroscopic (relative to the gas molecules) will acquire enough energy to surmount the potential peak is entirely a matter of chance — the chance that successive impacts will give it enough energy. And these impacts are entirely uncorrelated. An impulse in one direction is just as likely as not to be followed by a second impulse in the same or the opposite direction. One way of constructing non-white noise is to suppose that, instead, there is a time-correlation between successive impulses.

At this stage, it may be remarked that fiddling with the time-correlation offers a ready but trivial way of solving the microtubule problem: simply postulate that all the external impulses are in the same direction, and the particle in the sawtooth will move only in that direction. But that, of course, is simply a way of concealing the interesting question, which is whether it is possible to extract useful work from impulses due to noise that are symmetrical in their direction and on the average zero.

The authors discuss the general case in formal terms, but there is no general solution. Their real interest is to specify non-white noise that can be handled algebraically. The case that proves amenable to treatment is that in which the noise exerts either a positive or a negative force on the particle in the sawtooth, and switches from one state to the other at random times determined by a decreasing exponential function. In other words, the force due to the non-white noise is either in one direction or the other, and each state is converted into the other as if by radioactive decay.

Given that the two different states have the same half-lives, the time-average of the forces due to noise is evidently zero, while the forces are symmetrical. The only asymmetry in the problem is the shape of the sawtooth potential in which the particle is trapped. But the calculations show that there is a net movement of particles in one direction along the periodic sawtooth. Interestingly, the direction is that away from the steepest sawtooth edge. Not surprisingly, the magnitude of the non-white force must exceed a certain minimum before there will be any movement. It may be important that the maximum rate of transport is not that when the non-white forces are very large, but at some intermediate value related to the geometry of the sawtooth.

But what has this to do with the real world? That is what muscle physiologists and others will be asking. But this one illustration that strictly symmetrical non-white noise can provoke asymmetrical movement along an asymmetrical sawtooth may be more relevant than it seems.

All these biomechanical processes appear to be driven by the energy of the hydrolysis of ATP at catalytic sites carried by the molecules involved, which are presumably the source of the non-white noise forces. On the face of things, there is no reason to expect that to be a process favouring one direction of movement rather than the opposite. On the other hand, there is every reason why the non-white forces should be correlated in time; the hydrolysis of consecutive ATP molecules must be limited at least by the time they take to diffuse to the catalytic sites, for example.

Even so, the authors are commendably modest in their claims. "Whether or not nature takes advantage of this kind of effect at the subcellular level," they say, "remains to be seen."

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