

17.2: Passive vs Active Transport

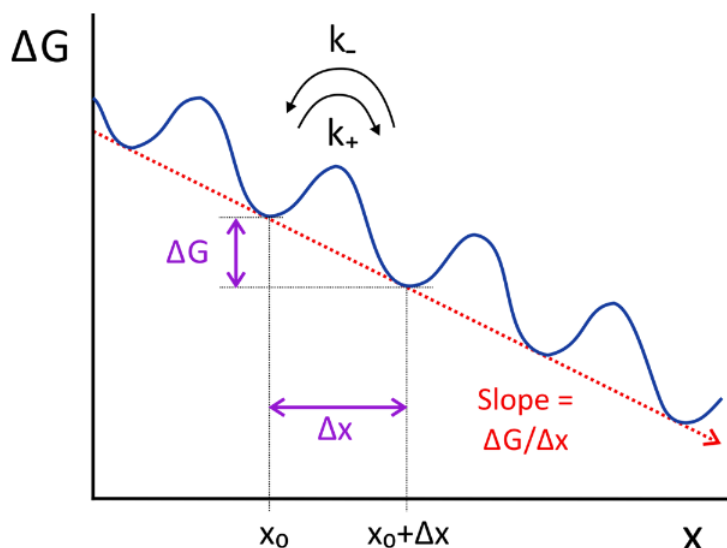
Directed motion of molecules in a statistically deterministic manner (i.e., $\bar{x}(t) = \bar{v}t$) in a thermally fluctuating environment cannot happen spontaneously. It requires a free energy source, which may come from chemical bonds, charge transfer, and electrochemical gradients. From one perspective, displacing a particle requires work, and the force behind this work originates in free energy gradients along the direction of propagation

$$w = - \int_{path} f dx \quad f_{rev} = \frac{\partial G}{\partial x}$$

An example of this is steady-state diffusion driven by a spatial difference in chemical potential, for instance the diffusion of ions through a membrane channel driven by a transmembrane potential. This problem is one of passive transport. Although an active input of energy was required to generate the transmembrane potential and the net motion of the ion is directional, the ion itself is a passive participant in this process. Such processes can be modeled as diffusion within a potential.

Active transport refers to the direct input of energy into the driving the moving object in a directional manner. At a molecular scale, even with this input of energy, fluctuations and Brownian motion remain very important.

Even so, there are multiple ways in which to conceive of directed motion. Step-wise processive motion can also be viewed as a series of states along a free energy or chemical potential gradient. Consider this energy landscape:



Under steady state conditions, detailed balance dictates that the ratio of rates for passing forward or reverse over a barrier is dictated by the free energy difference between the initial and final states:

$$\frac{k_+}{k_-} = e^{-\Delta G/k_B T}$$

and thus the active driving force for this downhill process is

$$f \approx -\frac{\Delta G}{\Delta x} = \frac{k_B T}{\Delta x} \ln \frac{k_+}{k_-}$$

This perspective is intimately linked with a biased random walk model when we remember that

$$\frac{k_+}{k_-} = \frac{P_+}{P_-}$$

If our free energy is the combination of a chemical process (ΔG_0) and an external force, then we can write

$$\frac{k_+}{k_-} = \exp[-(\Delta G_0 + f\Delta x)/k_B T]$$

Feynman's Brownian Ratchet

Feynman used a thought experiment to show you cannot get work from thermal noise.¹ Assume you want to use the thermal kinetic energy from the molecules in a gas, and decide to use the collisions of these molecules with a vane to rotate an axle. The direction of rotation will be based on the velocity of the molecules hitting the vane, so to assure that this rotation proceeds only one way, we use a ratchet with a pawl and spring to catch the ratchet when it advances in one direction.

This is the concept of rectified Brownian motion.

At a microscopic level, this reasoning does not hold, because the energy used to rotate the ratchet must be enough to lift the pawl against the force of the spring. If we match the thermal energy of gas $T = \frac{1}{2}m\langle v_x^2 \rangle$ to the energy needed to raise the pawl $U = \frac{1}{2}\kappa x^2$ we find that the pawl will also be undergoing fluctuations in x with similar statistics to the bombardment of the vane $\kappa = \sqrt{mk_B T / \langle x^2 \rangle}$. Therefore, the ratchet will instead thermally diffuse back and forth as a random walk. Further, Feynman showed that if you imbedded the vane and ratchet in reservoirs of temperature T_1 and T_2 , respectively, then the ratchet will advance as desired if $T_1 > T_2$, but will move in reverse if $T_1 < T_2$. Thus, one cannot extract useful work from thermal fluctuations alone. You need some input of energy—any source of free energy.

1. http://www.feynmanlectures.caltech.edu/I_46.html

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