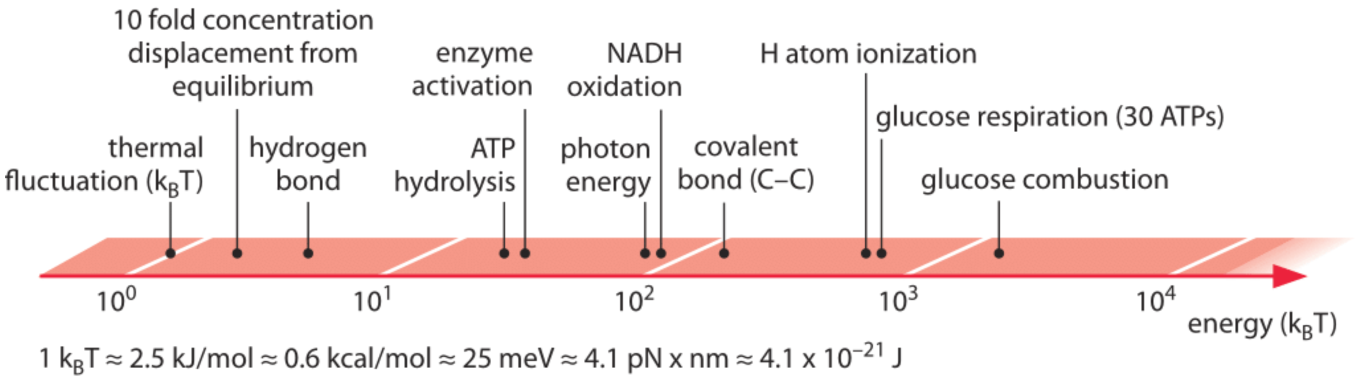
Energies and forces

In the two previous notebooks, we have discussed lengths, volumes, and concentrations. Other critical aspects are energies and forces. In the our every day world, sources of useable energy are often electric, gravitational, or derive from combustion engines. At the cellular scale, energy is exchanged in very different "currencies" and it is important to develop some intuition for it.

The most important energy scales for our purposes are

- the thermal energy scale kT: transitions that require energy on the order of kT happen spontaneously, are undirected, and evade control.
- ATP hydrolysis: the most important energy currency of biology
- Energy of a photon of visible light



source: Physical Biology of the Cell.

The thermal energy kT

As you recall from thermodynamics, the probability to observe a particular microstate is proportional to its Boltzmann factor

$$\sim e^{-\frac{\Delta E}{kT}}$$

where kT is the thermal energy scale at temperature T. Whether an energy difference ΔE between two states is smaller or larger than kT determines whether transitions happen spontaneously, are reversible, require large activation energies, etc.

Almost all processes at the nanoscale depend critically on how their energy scales compare to kT. It is therefore useful to know the value of kT in various units.

$$kT \approx 0.025eV \approx 0.6kcal/mol \approx 2.5kJ/mol \approx 4pN \times nm$$

(note: all of these have the dimension `energy` , expressed in different units)

Chemical energies in biology

Depending on the conditions, hydrolysis of one molecule of ATP liberates about 12kT of usable energy.

$$ATP + H_2O \rightarrow ADP + P_i \quad \text{yields} \quad -30kJ/mol \approx -12kT$$

Guestimation

How much force can a molecular motor exert?

source: Cell Biology by the numbers

To estimate the maximal force, recall that

"Work = Force x Distance".

To estimate the force, note that we know roughly the amount of energy (work) available to the motor (one ATP hydrolysis). Motors like myosin or kinesin walk on cytoskeletal filaments and take steps of about 10nm.

$$F = \frac{12kT}{10nm} = \frac{48pNnm}{10nm} \approx 5pN$$

Membrane potentials are maintained by molecular motors

ATP-Synthase, wikipedia

How efficient is the ATP-Synthase?

Moving an H^+ ion across a membrane with potential difference ΔV requires energy of $e\Delta V$.

$$100meV \approx 4kT$$

Now recall that hydrolysis of ATP liberates about $12kT$ usable energy. The proton-pump/ATP-synthase couples the transport of three protons to the hydrolysis/synthesis of one ATP molecule -- a process at near 100% efficiency!

[see Yasuda et al for more detail (https://www.cell.com/fulltext/S0092-8674(00)](https://www.cell.com/fulltext/S0092-8674(00)81456-7)

Additional resources

- Biology by the Numbers (https://www.dropbox.com/s/gvpleqtcv8scro4/cellBiologyByTheNumbersJuly2015.pdf?dl=1) by Milo and Phillips, Chapter 3

Dig deeper

- To how many ATP equivalents corresponds the energy of photon of visible light?
- How efficient is photosynthesis?
- How does it compare to solar panels?

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