Energy, Equilibrium & Cells:

~~4 Key Kinds of Energy in Biology~~:

① Chemical Energy — bonds

② Mechanical Energy — Potential Energy (springs)

③ Electromagnetic Energy — ions & electric potentials

④ Thermal Energy — random motion of atoms

• Thermal Energy is <u>significant</u> – random thermal jostling due to other molecules plays a large roll in determining a biomolecule's state.

<u>Scales</u>:

thermal $E = 1\ k_B T = 0.025\,eV = 0.6\ kcal/mol$

more <u>useful</u> unit

$$\boxed{k_B T = 4.1\ pN\ nm}$$

⇒ thermal energy generates forces on the order of 4 piconewtons over distances of nanometers

Motor proteins generate forces ~ 20 – 40 pN!

<u>Thus</u> thermal forces are on the same scale as the forces being made by cell's machinery

Other energies in k_BT:

- Covalent bond $\sim 2\,eV \sim 100\,k_BT$
- Hydrogen bond $\sim 0.2\,eV \sim 10\,k_BT$
- Burn 1 ATP $\sim 0.4\,eV \sim 20\,k_BT$

Fuel in Cells:

- Most molecular synthesis inside the cell is powered by the energy released from breaking chemical bonds
- Largest source of stored energy is in the molecule ATP (adenosine-tri-phosphate)
- Energy is released when ATP → ADP + P

$$ATP \rightarrow ADP + P + 20\,k_BT$$

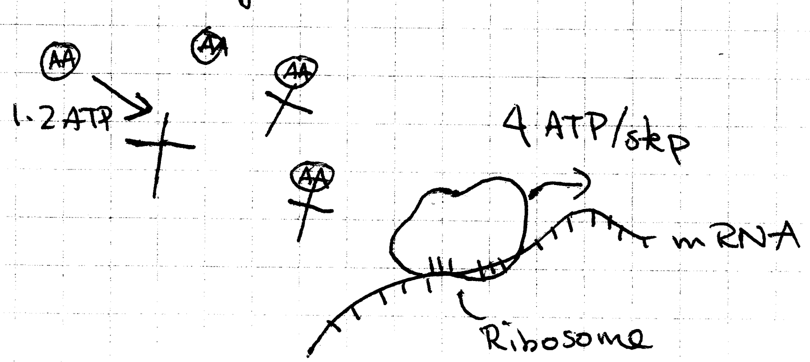
- ATP is made by breaking down glucose

in E. coli: 1 glucose + O_2 → 30 ATP

in mitochondria: 1 glucose + O_2 → 20 ATP

anaerobic: 1 glucose → 2 ATP

Making Protein:



- 1.2 ATP to add AA to tRNA

+ 4 ATP for each Ribosome step

≃ 5 ATP for each AA in a protein

Q: How much ATP to make all the protein in E. Coli?

avg protein = 300 AA $\quad N_{protein} = 3\times10^6$

so $N_{ATP} = (5\ ATP/AA)(300\ AA)(3\times10^6) \simeq 45\times10^8\ ATP$

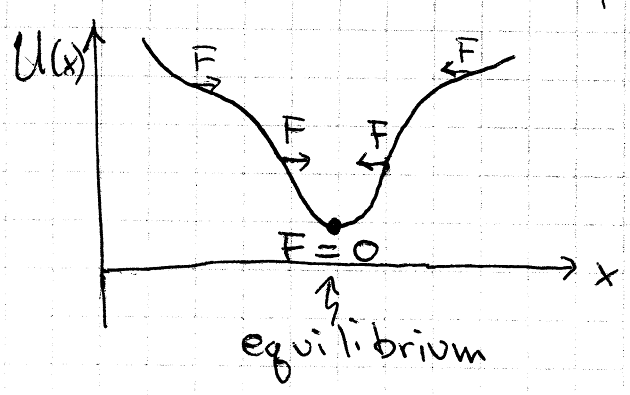
- Total amount of ATP needed to drive processes in E. Coli ~ 2×10^{10} ATP
- This corresponds to ~ 6×10^8 glucose to make ATP
- Compare this amount of glucose, to the amount of glucose needed to make all of the cell's material (Assignment #1)

Equilibrium & Energy Minimization:

Recall:

Mechanical Equilibrium $\Rightarrow \Sigma\vec{F} = 0$

- or in terms of potential energy



- $F = -\dfrac{dU}{dx}$

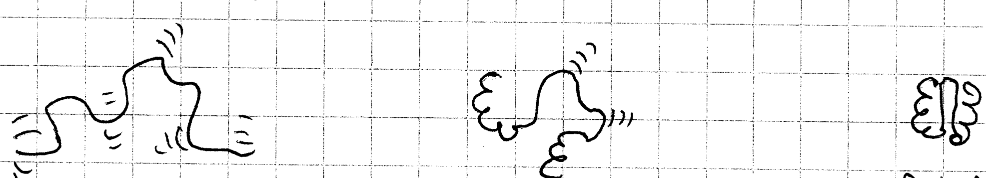
- Mechanical equilibrium occurs at the minimum of the potential energy
- Particle will relax to the position where it at a minimum of $U(x)$

Q: Can the cell be treated as an equilibrium system?

A: Sometimes. The cell is constantly doing something dynamic and so by definition is not in equilibrium. However, given a certain timescale, some processes may be in equilibrium.

e.g. crawling cell – the dynamics of the cell's membrane is much faster than its cytoskeleton. So the membrane is in equilibrium with respect to the forces pushing on it from the cytoskeleton.

Protein Folding & Free Energy

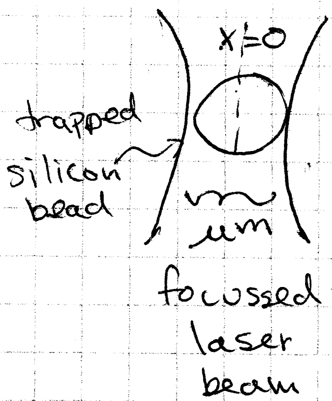


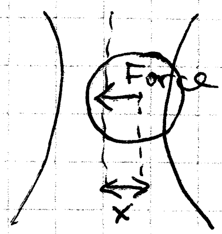
open	globular	folded
High Entropy	Mix of Entropy & Energy	Mostly Energy
$F_o = -TS$	$F_g = E - TS$	$F = E$

- Which fold is the ground state? Depends on T
- Low T → folded state has lowest F
- High T → $-TS$ wins and open state has lowest F

Optical Tweezers:

- Can measure the forces of single biomolecules and watch how they fold

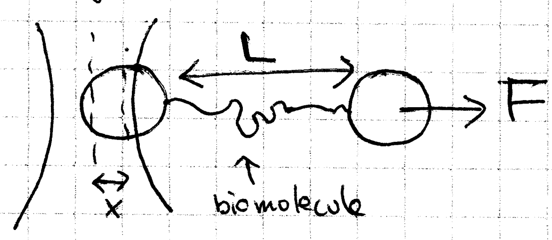




Bead experiences force when moved from center of trap

$$U_{trap} = \frac{1}{2} k_{trap} x^2$$

- Pulling on a molecule



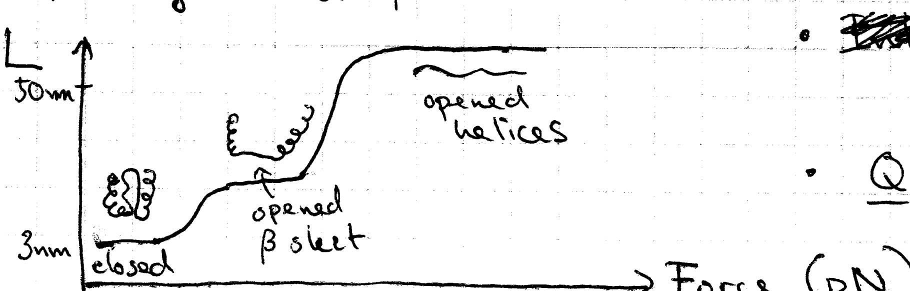
- $U(x) = \frac{1}{2} k x^2 - Fx$ (Fx: work done against force)

- equilibrium? $\frac{dU}{dx} = 0 \rightarrow x_{eq} = \frac{F}{k_{trap}}$

- Thus by looking at x_{eq} you can figure out what is the F applied.

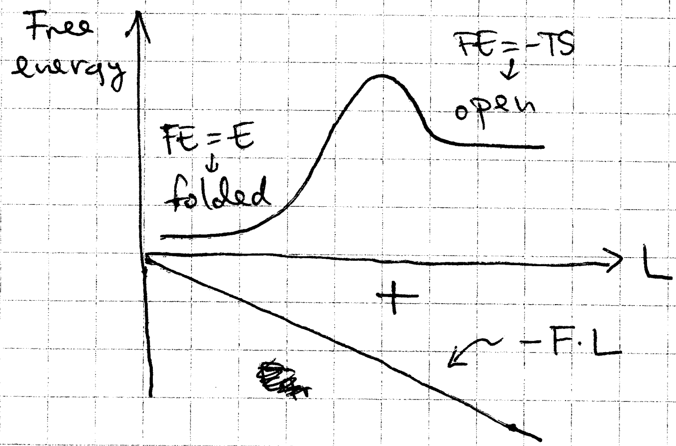
- Then, measure L (length of molecule) as a function of F

- e.g. Pulling on a protein

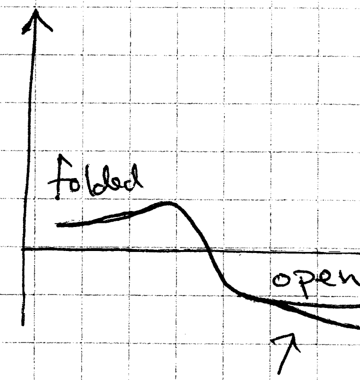


- Can also watch it refold
- Q Does it follow the same path?

In terms of free energy:



Pull with a force, F ⇒



so now the open state is the minimum of the total free energy