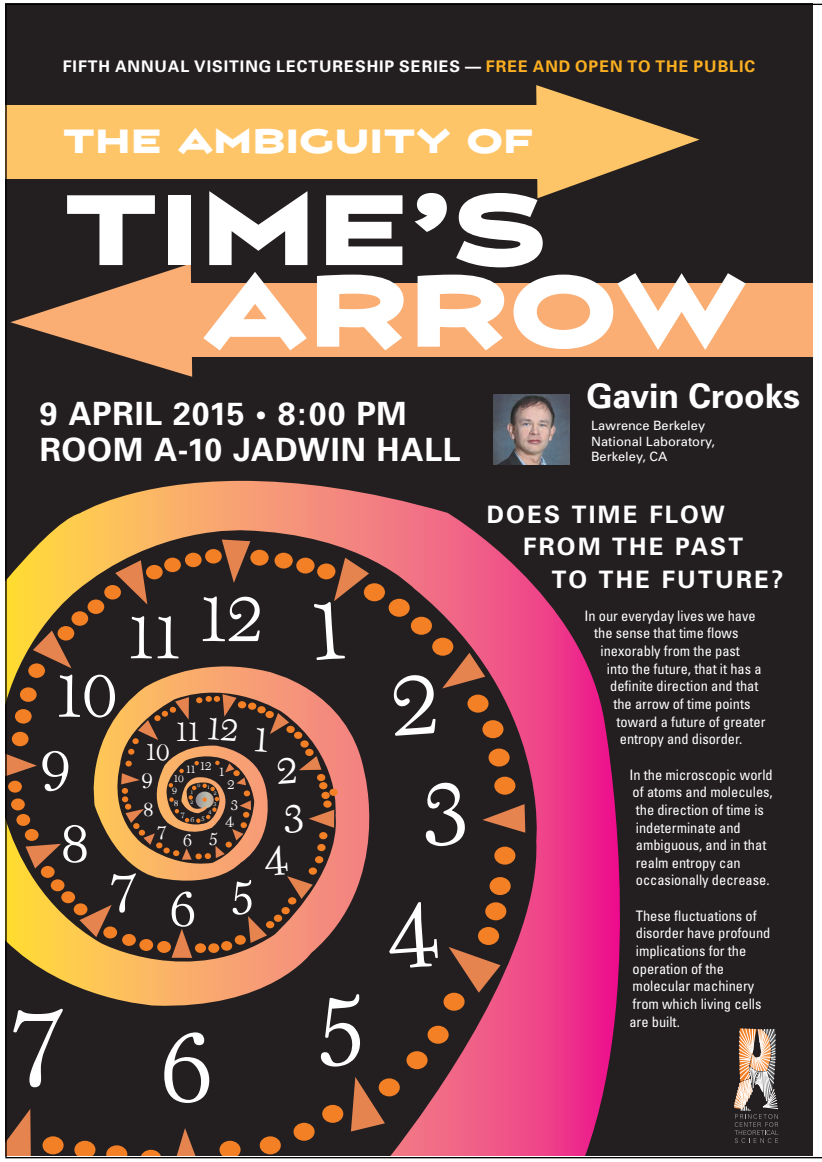
Forward Through Backwards Time by RocketBoom



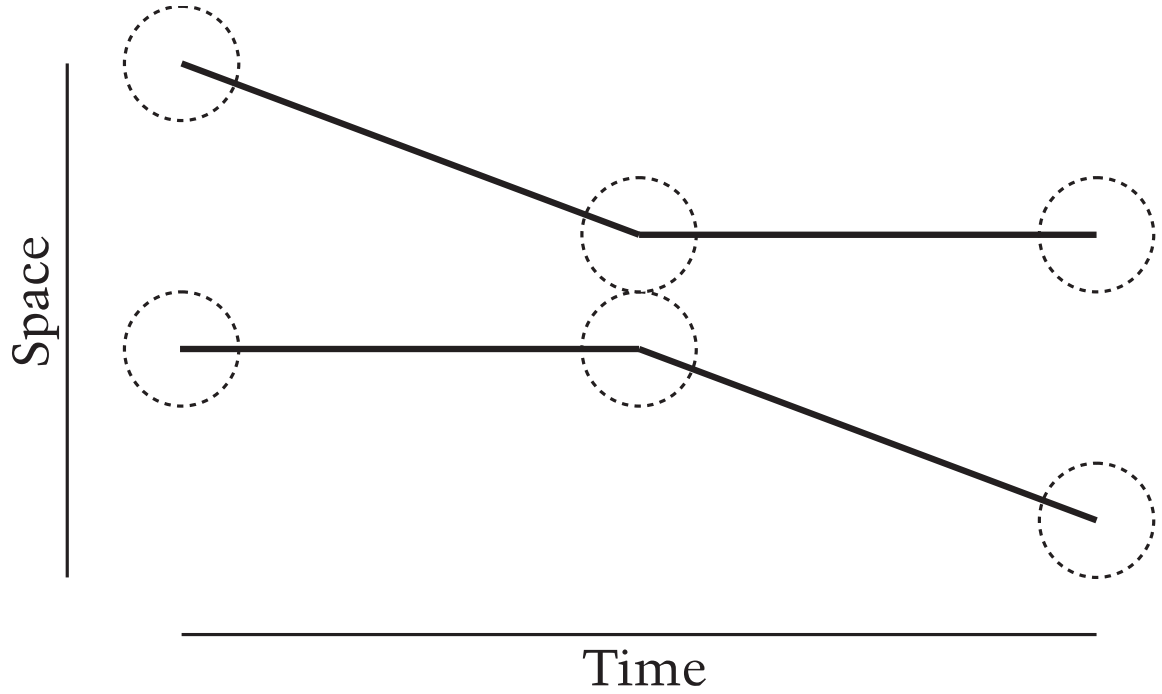
The Ambiguity of Time's Arrow

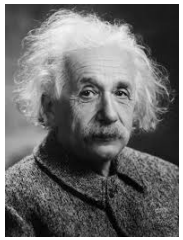
Dr. Gavin Crooks

BERKELEY LAB
LAWRENCE BERKELEY NATIONAL LABORATORY

Time flies like an arrow. Fruit flies like a banana.

Fundamental Dynamical Laws of Physics are Time Reversal Symmetric *





People like us, who believe in physics, know that the distinction between past present and future is only a stubbornly persistent illusion

-- Albert Einstein

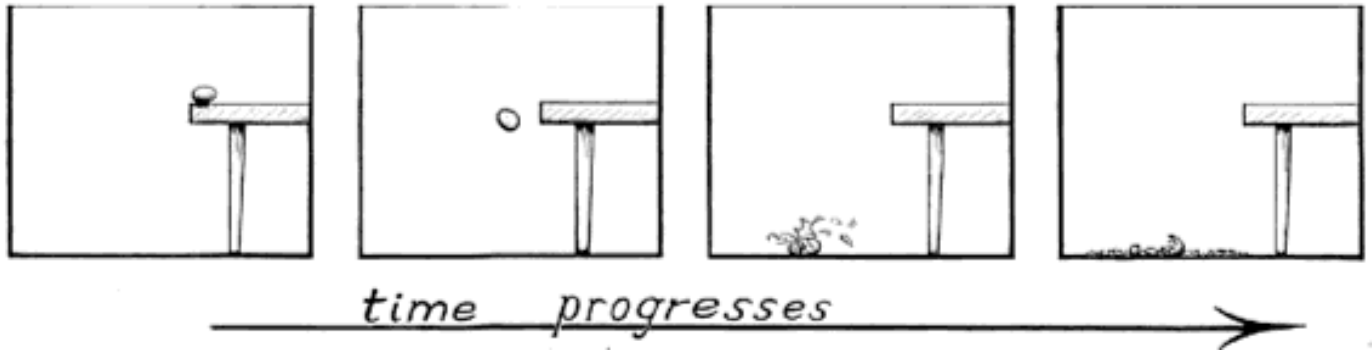
The 2nd Law of Thermodynamics

Clausius inequality (1865)

$$\Delta S_{\text{total}} \geq 0$$

Entropy

Entropy increases as time progresses



Cycles of time
R.Penrose (2010)

Once or twice I have been provoked and asked the company how many of them could describe the Second Law of Thermodynamics. The response was cold. It was also negative. Yet I was asking something which is about the scientific equivalent of "Have you read a work of Shakespeare's?"

-- C. P. Snow

What is Entropy?

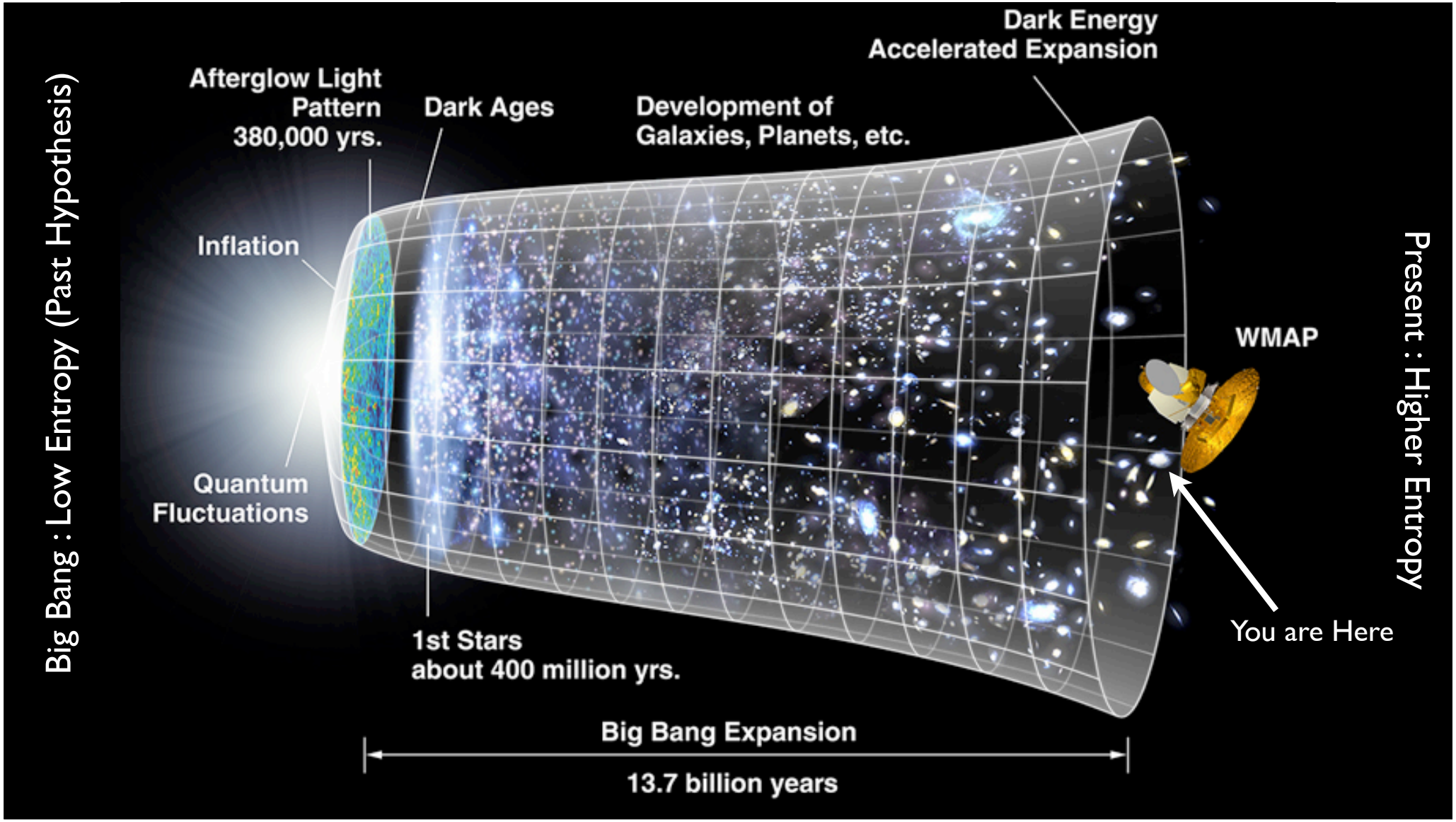
$$S = \log\{\text{Number of configurations}\}$$

1 natural unit of entropy
equivalent to
1 kT of thermal energy

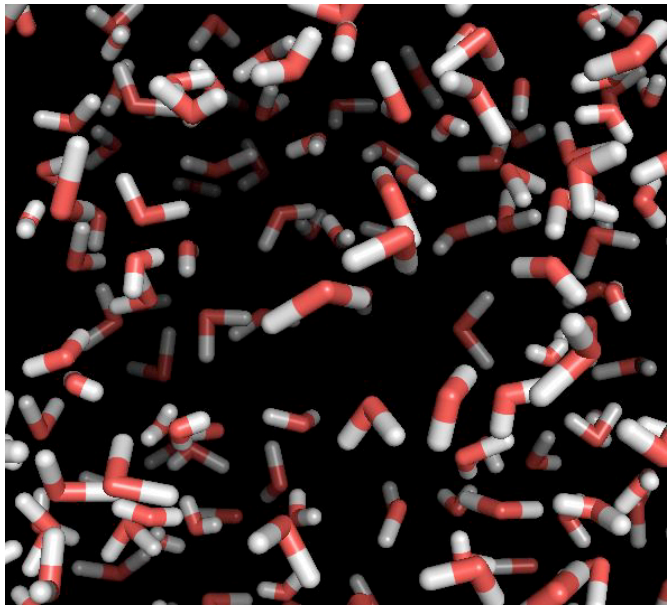
T : Temperature (ambient 300 Kelvin)
k : Boltzmann's constant

1 kT = 25 meV
= 2.5 kJ/mol

average kinetic energy = 3/2 kT


Big Bang : Low Entropy (Past Hypothesis)
Present : Higher Entropy
Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
You are Here
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Thermodynamic Equilibrium



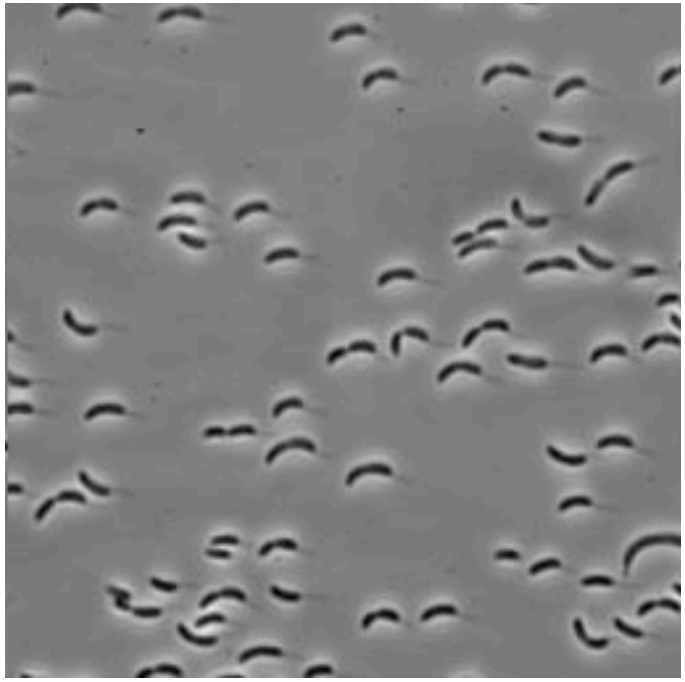
No change in Entropy. No Arrow of time.
Future, past and present are indistinguishable

What is Life?

Thermodynamic Equilibrium

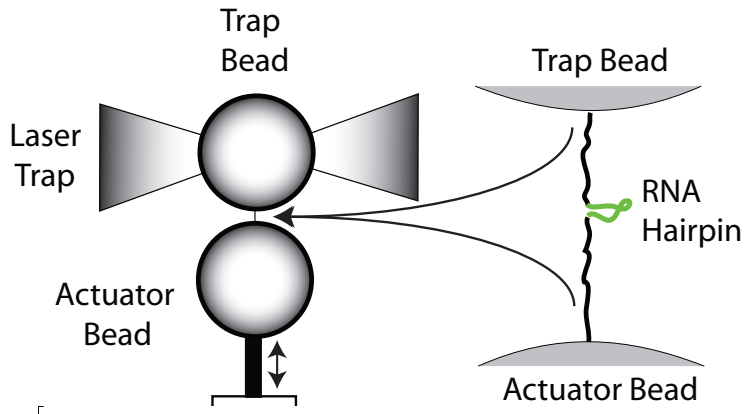
Future, past and present are indistinguishable

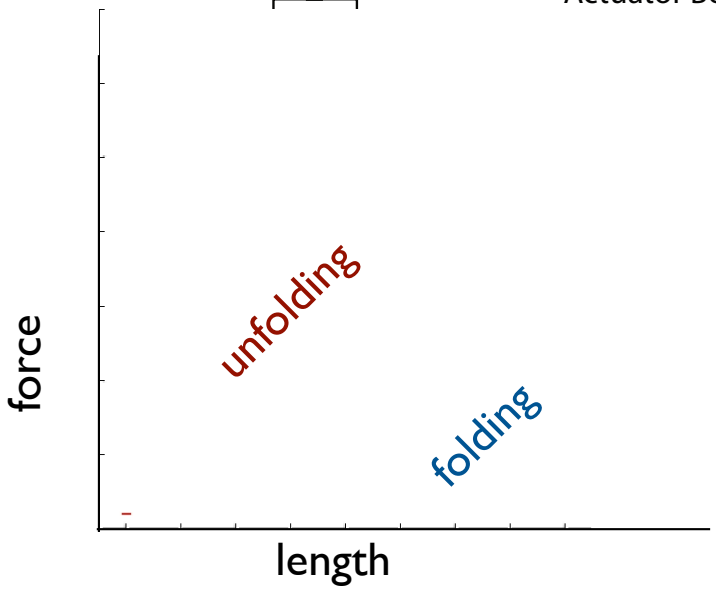
Life



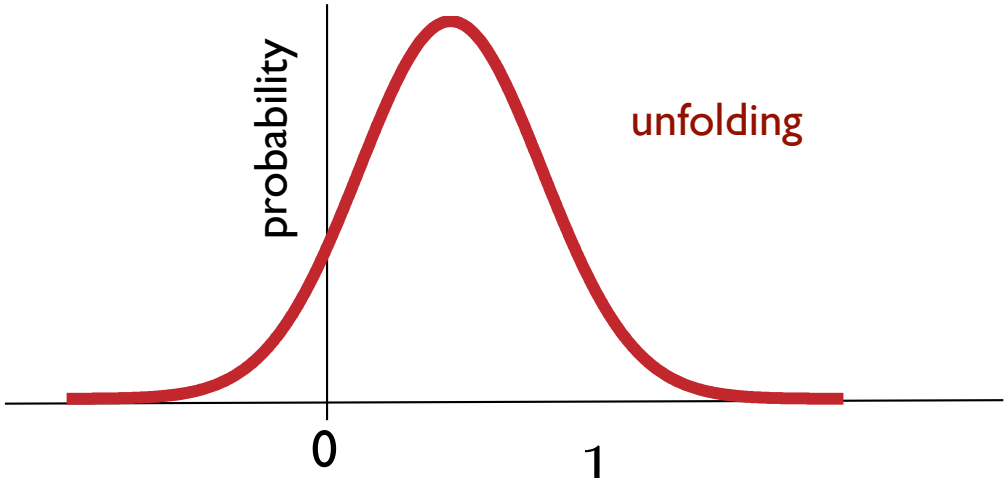
Life's imperative: Make tomorrow look very different from today

Unfolding of RNA hairpins.





Entropy sometimes goes down!



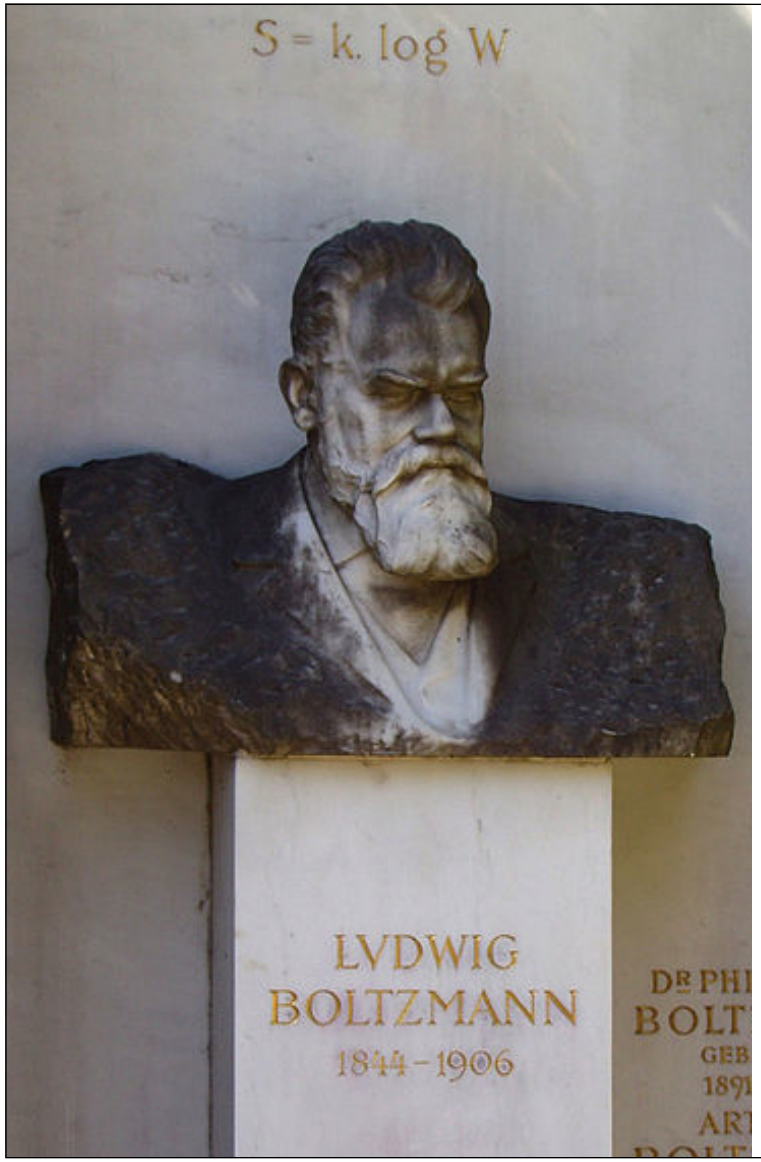
$$\Delta S_{\text{total}} = \frac{1}{T}\left(W - \Delta F\right)$$

total entropy change

temperature

work

free energy change

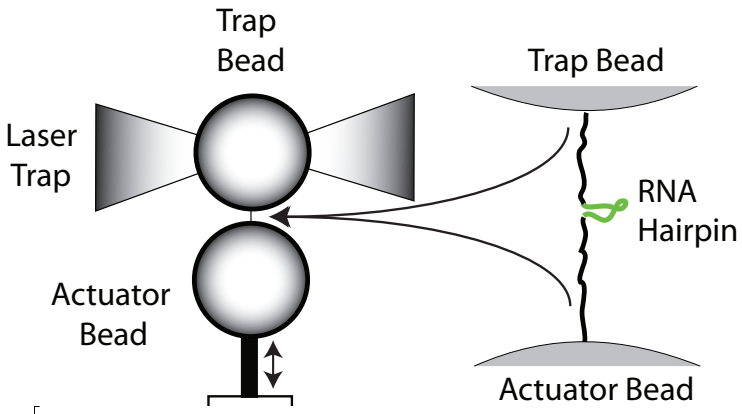


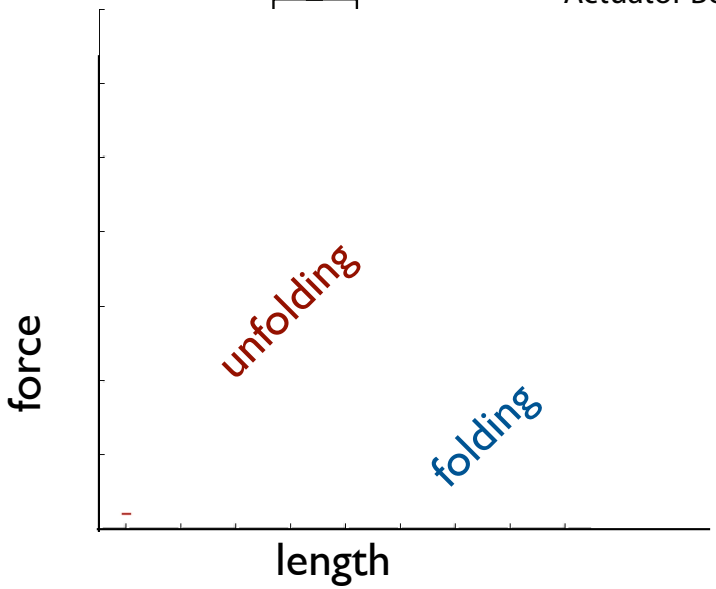
Ludwig Boltzmann (c1890)

We cannot speak of a direction of time as a whole, only certain directions of time have directions, and these directions are not all the same.

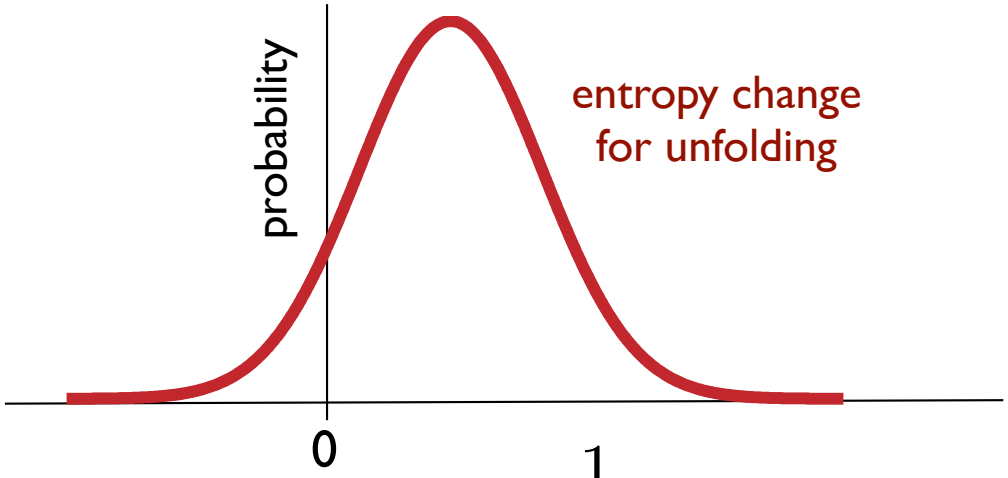
--- Hans Reichenbach (paraphrasing Boltzmann)

Unfolding of RNA hairpins.





$$P(\text{unfolding}) = \frac{1}{1 + e^{-\Delta S_{\text{total}}}}$$



$$\Delta S_{\text{total}} = \frac{1}{T}(W - \Delta F)$$

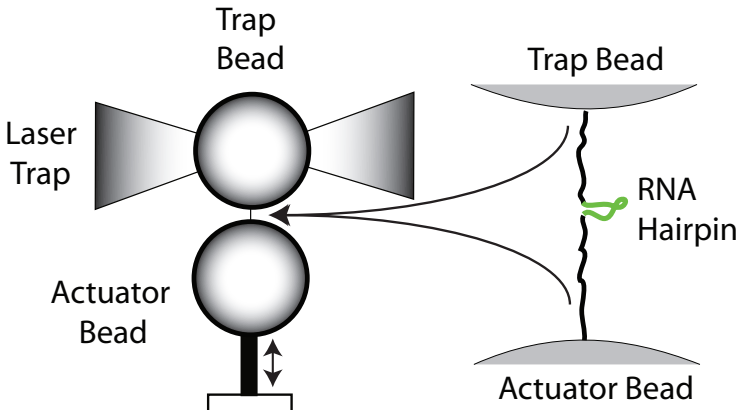
total entropy change

temperature

work

free energy change

The (Refined) 2nd Law of Thermodynamics

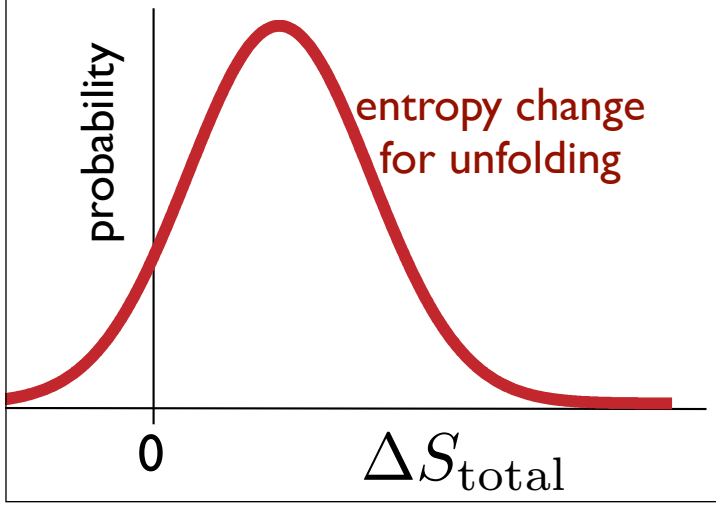


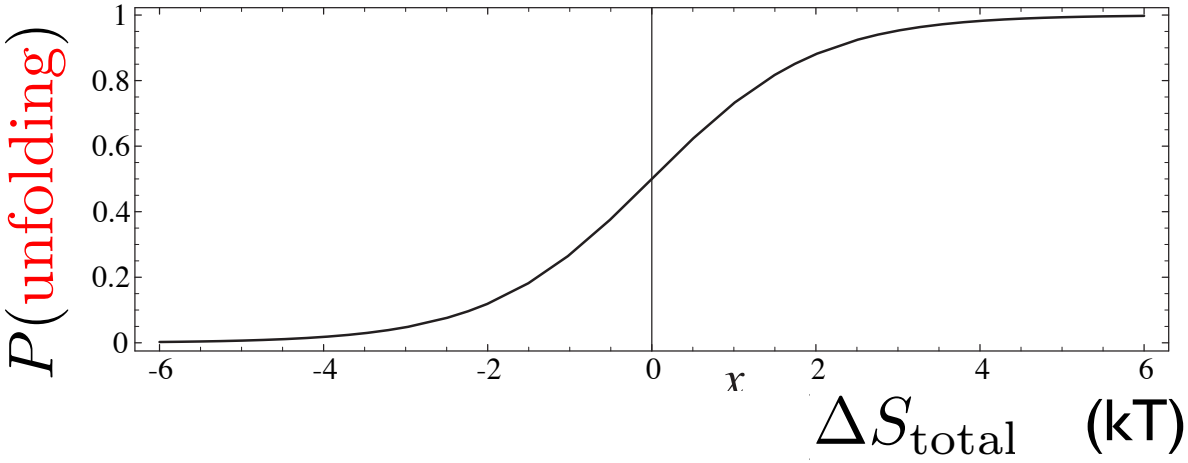
$$\langle \Delta S_{\text{total}} \rangle \geq 0$$

total entropy increases on average

$$P(\text{unfolding}) = \frac{1}{1 + e^{-\Delta S_{\text{total}}}}$$

The arrow of time is ambiguous (for small entropy changes)

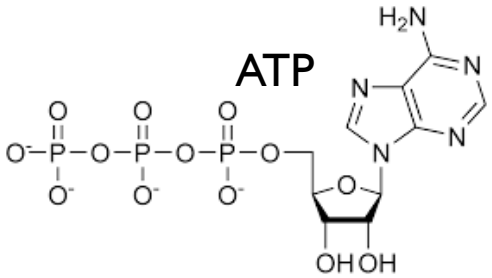




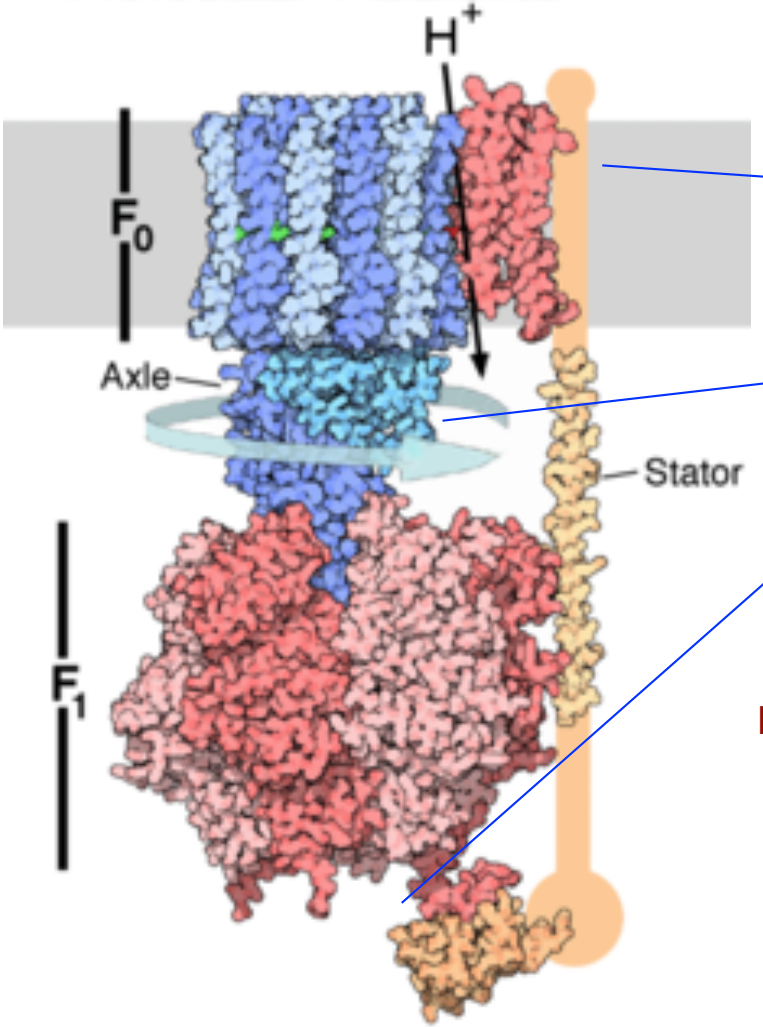
Molecular Machines

Mitochondria

ATP



ATP Synthase



proton gradient

mechanical energy

chemical energy

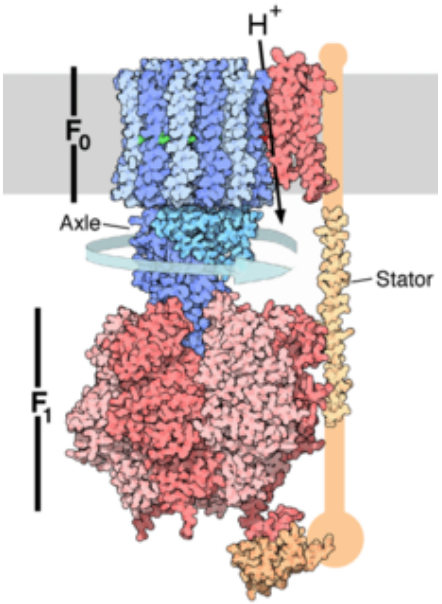
Free Energy ATP = 20 kT
= 0.5 eV

1 kT = 25 meV

= 2.5 kJ/mol

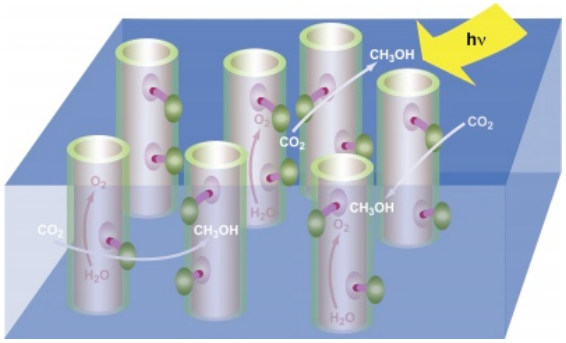
Frontiers of thermodynamics

$$\langle e^{-\Delta S_{\text{total}}} \rangle = 1$$

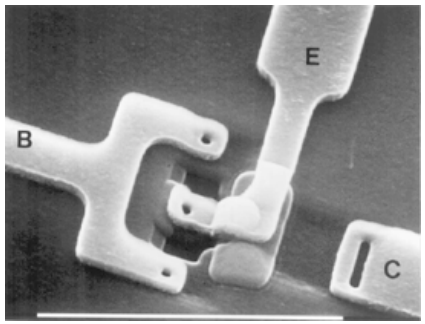


ATP synthase

biological molecular machines



nano-scale engineering



computers