

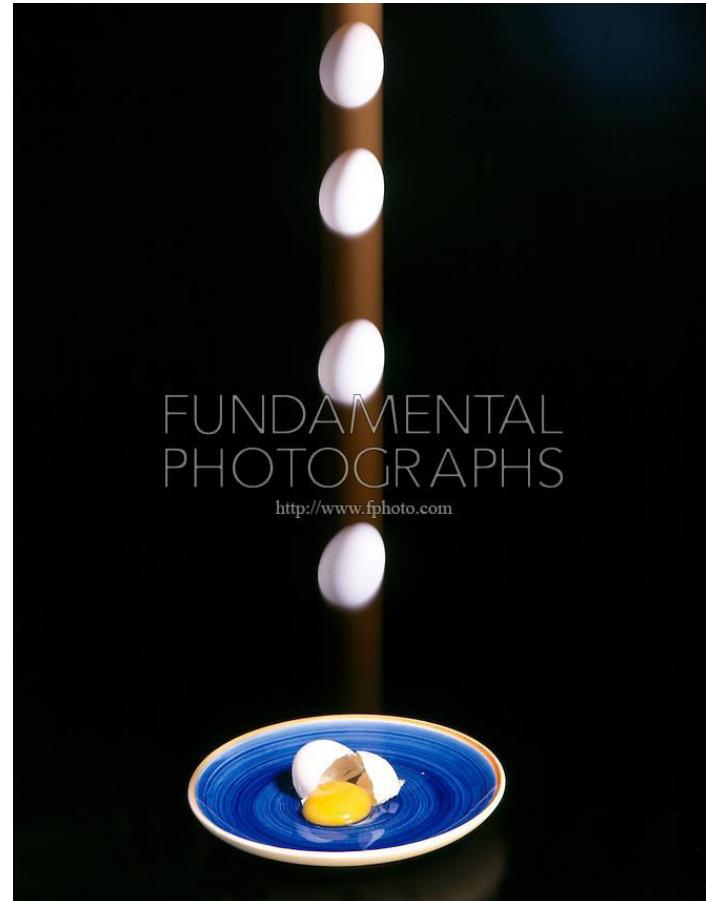
# Introduction

- Energy is the “lifeblood” of the universe.
- It can flow from place to place, or change its form, but the total amount of energy is always **conserved** (remains **constant**). Energy **never runs out**. Energy is **eternal**.



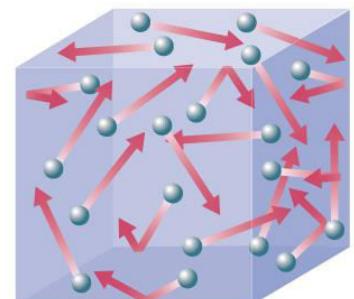
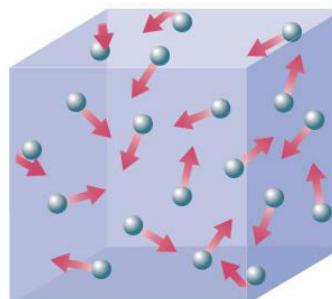
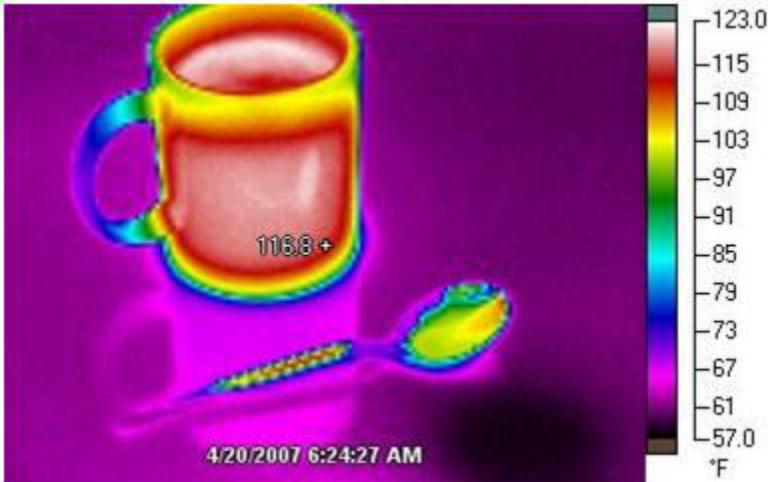
# Introduction

- Every physical process obeys the law of **conservation of energy**.
- But it's easy to imagine processes that obey this law that **don't** actually happen.
- E.g.: the expanding sound waves of the egg cracking could reverse, and travel backwards, converging on the egg, and the smashed egg could reform and fly up off the plate. This wouldn't violate conservation of energy, but it never happens. **Why not?**
- What is the origin of this apparent **time asymmetry** in the way nature works?



# Introduction

- **Simpler example:** When a hot cup of coffee cools to room temperature, thermal energy flows from the coffee molecules to the air molecules, in a way that **conserves total energy**.
- The **reverse** process also conserves total energy, but **never happens**. The energy *could* flow back into the coffee, but it never does. Why not? Why does energy spontaneously flow from hot to cold, but **not from cold to hot**?
- There must be *another* law at work, beyond conservation of energy. This other law seems to involve the **direction of flow** of energy, or how energy tends to **distribute** itself.

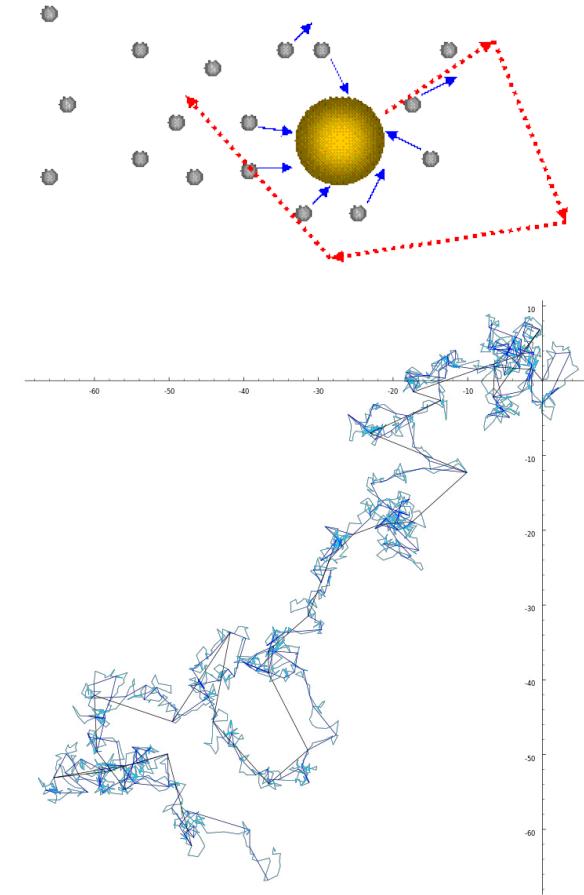
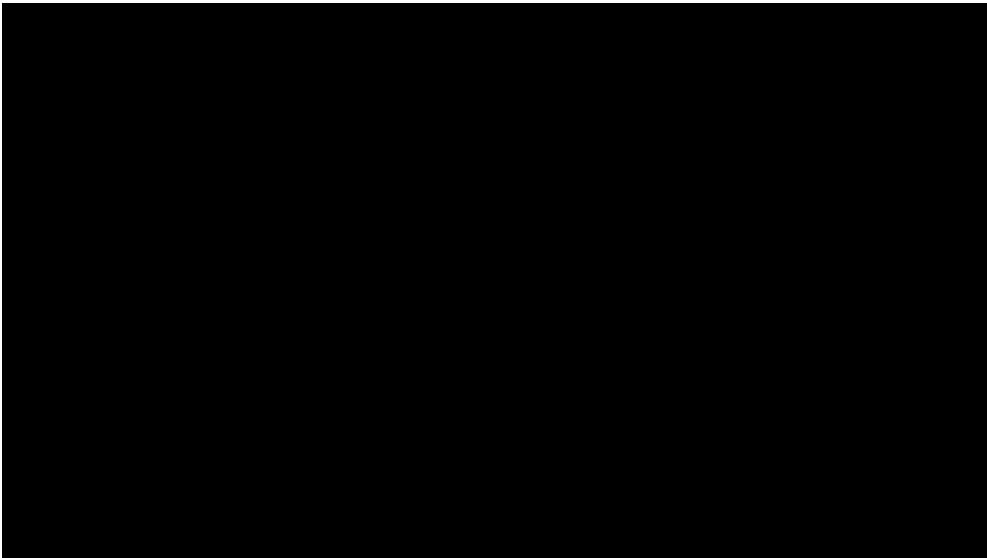


Longer arrows mean higher average speed.

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# Brownian Motion

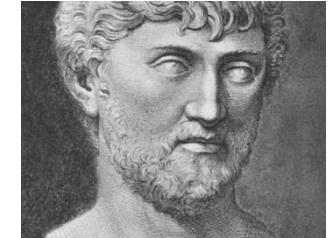
- **Brownian motion** is a “*random walk*” of a larger particle resulting from its collisions with smaller, surrounding atoms or molecules that are in random thermal motion.



# Brownian Motion

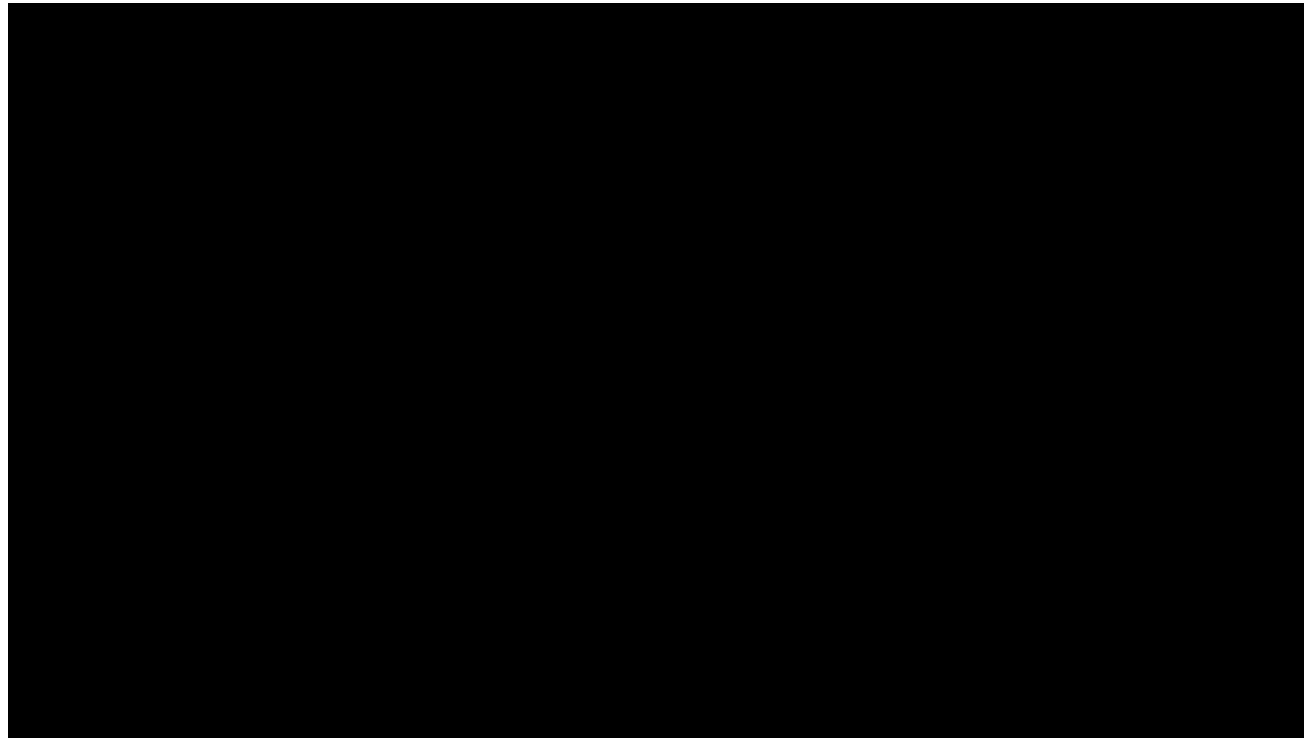
## History:

- **Lucretius** (c. 60 BC), *On the Nature of Things* ([listen to CBC podcast](#)): Used the random motion of dust motes in a shaft of sunlight as evidence for Democritus' idea of atoms (essentially *right!*).
- Named after the botanist **Robert Brown** who, in 1827, observed similar random motion of pollen grains in water.
- Mathematical descriptions began in the late 1800s; **Einstein** (1905) made a detailed **quantitative** analysis of Brownian motion that provided definitive confirmation that atoms and molecules actually exist.
- **Diffusion:** 
$$\frac{\partial \rho}{\partial t} = D \frac{\partial^2 \rho}{\partial x^2}$$



# Brownian Motion

## Einstein & Brownian Motion



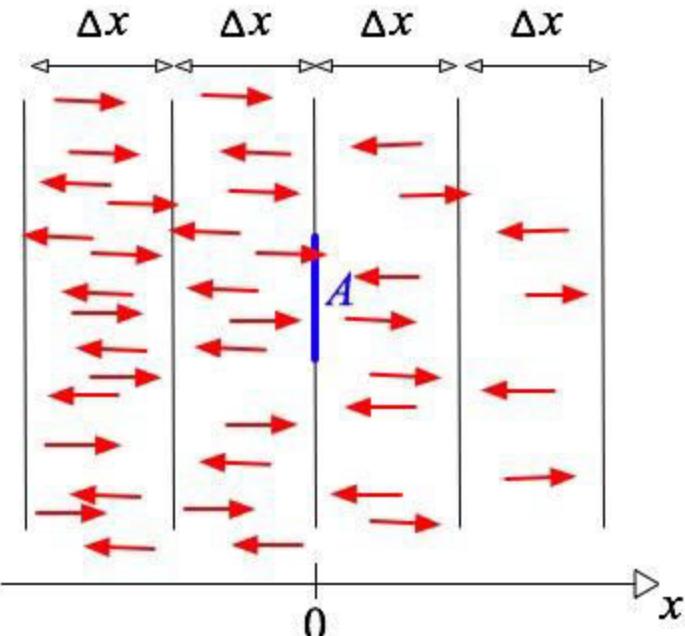
# Diffusion

- **Diffusion** is the net migration of particles from a region of **high** concentration to a region of **low** concentration.



# Diffusion

- **Diffusion** is the net migration of particles from a region of **high** concentration to a region of **low** concentration.
- Diffusion is similar to Brownian motion: Each particle moves **independently** of the others, in **purely random** thermal motion. So *why is there a **net migration** from higher to lower concentration?*
- **Diagram:** Particles in any one layer are equally likely to move left as right. There is a **net** motion to the right simply because there are *more particles to the left of area A* (about half of which move right), *than particles to the right of A* (about half of which move left).

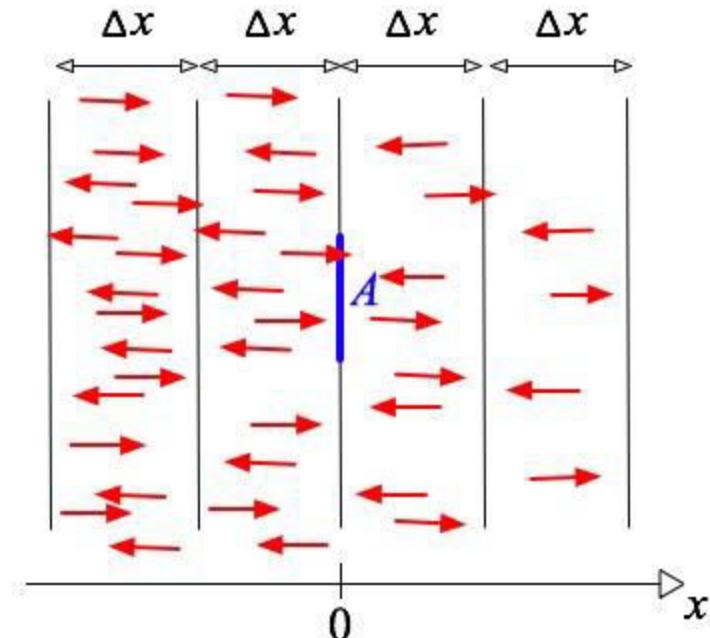


$$\frac{\partial \rho}{\partial t} = D \frac{\partial^2 \rho}{\partial x^2}$$

**“Law from lawlessness”**

# Diffusion

- Diffusion continues until there is an **equal** concentration of particles in all layers  $\Rightarrow$  **equal** number randomly moving right or left through any area A.
- Called **dynamic equilibrium** (vs. static): Particles continue their incessant “random walking”, but on average the concentration remains uniform.

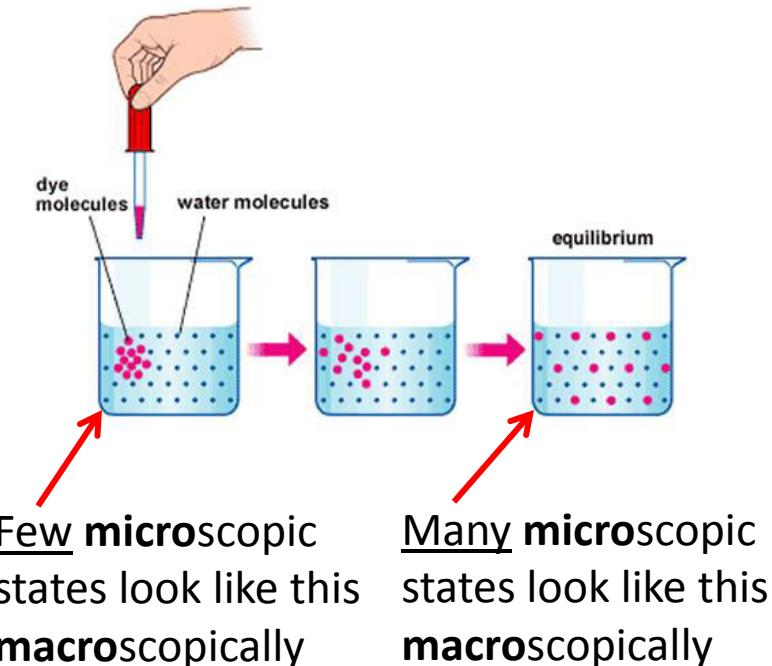


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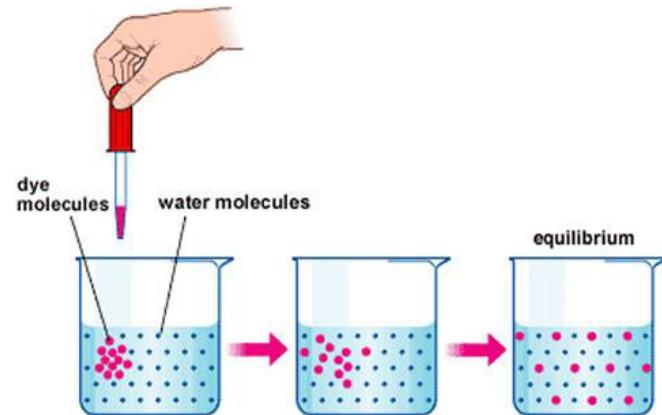
# Diffusion

- Nature has **no inherent preference** for one state over another. There are simply **many more** ways for the particles to be spread out, than localized.
- Even a tiny amount of spreading opens up a **vast increase** in the number of nearby states like this, compared to the less spread out state it came from.
- The system **could** go back, but by the “law of large numbers” it will spend **virtually all** of its time “lost” in the huge new space of nearby, slightly more spread out states.
- This continues until **equilibrium**. There are **stupendously** more uniform-like states than even the slightly less uniform-like states a moment before. The system inexorably **ratchets** towards equilibrium.



# Diffusion

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There's **no reason** system can't go back to the original state. It's merely **stupendously unlikely**.

Process is **irreversible** just by the “**law of large numbers**”.

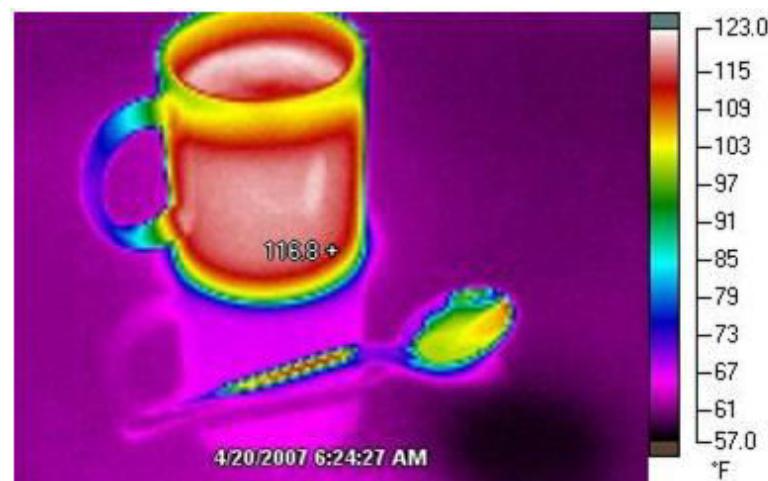
# Diffusion

No “physical law” governs this process. It is driven one way (and not the other) by purely random, purposeless thermal motion. Of all possible next states (of which nature *prefers none*), the **vast majority** are more spread out, so chances are the next state will be more spread out.



# Diffusion of Thermal Energy

- It's the same for the cup of coffee: There are simply **stupendously** more ways for the thermal energy to be spread uniformly throughout the [coffee + room air] than to be spread throughout the [coffee alone].
- There is nothing preventing the thermal energy flowing from the warmed air back into the room-temperature coffee, it's just **stupendously unlikely**.
- This **lawless/purposeless** tendency for particles or energy to spread out (disperse/diffuse) is called the **Second Law of Thermodynamics**. “Law from lawlessness”.



## Second Law

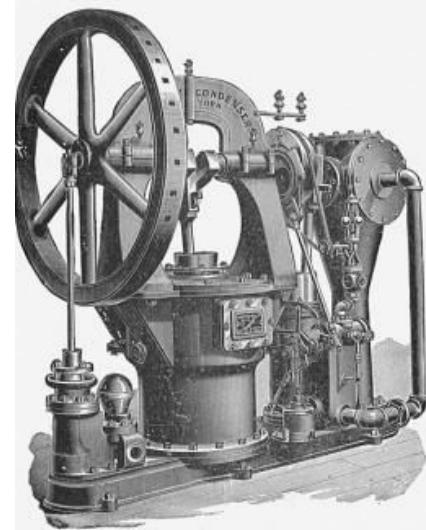
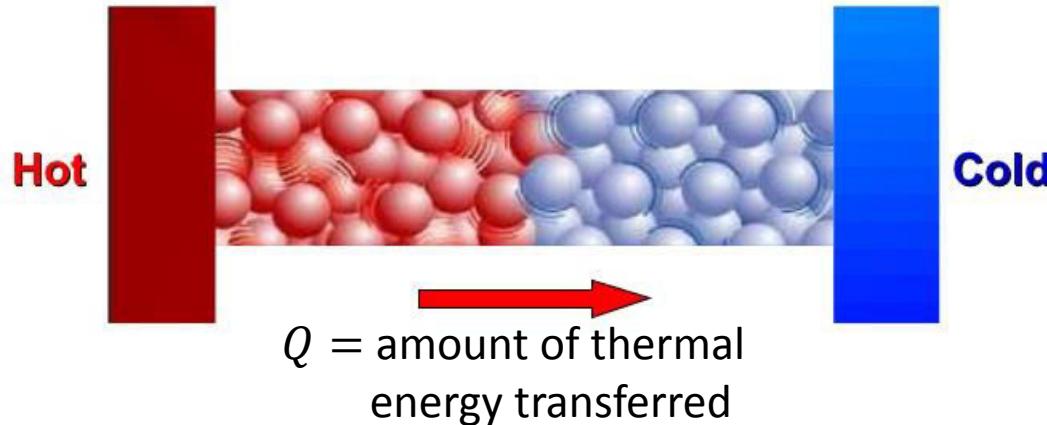
- **Second Law of Thermodynamics:** The entropy of an isolated system never decreases

This is perhaps the most potent statement in all of science, rivaled only by the first law of thermodynamics: the law of conservation of energy.

- Roughly speaking, “**entropy**” is a measure of “**disorder**”. The natural diffusion (or dispersion) of energy (or particles) increases the disorder in the universe. Disorder can decrease **locally** (e.g., life), but at the expense of **greater increase** in disorder **elsewhere**, so that the universe **as a whole** (or any isolated system within the universe) inexorably **ratchets towards greater disorder**, or higher entropy.
- While energy is **conserved** (and thus eternal), it is continually being **degraded** into a lower quality (more spread out) form. (Recall “heat death” of the universe.) While this might sound bleak, it is precisely this lawless, purposeless process that is responsible for virtually **all change** in the world, and (as we shall see) it is the very **engine of life itself!** It’s not energy, but **degradation of energy**, that “makes the world go round”.

# Entropy

- **Entropy** (denoted by the letter  $S$ ) was first understood in the context of the flow of thermal energy from a hot object to a cold object:



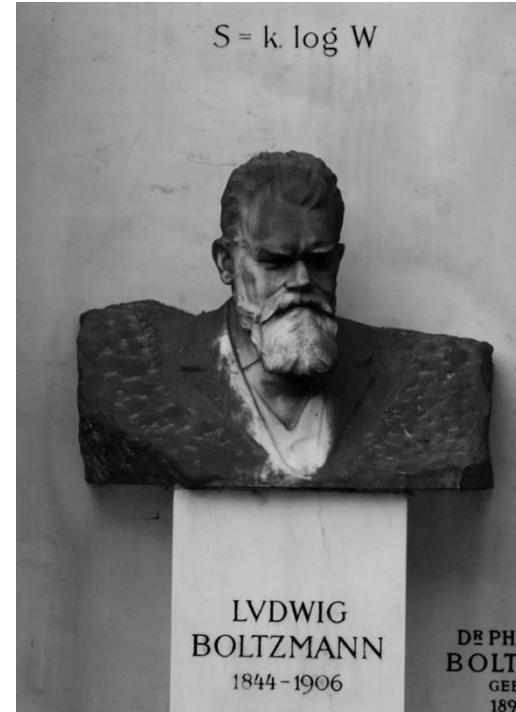
$$\Delta S = S_f - S_i = \frac{Q}{T} \quad \Delta S_{\text{hot}} = -Q/T_{\text{hot}} < 0 \text{ (entropy of hot object decreases)} \\ \Delta S_{\text{cold}} = +Q/T_{\text{cold}} > 0 \text{ (entropy of cold object increases)}$$

But  $T_{\text{hot}} > T_{\text{cold}} \Rightarrow \Delta S = \Delta S_{\text{hot}} + \Delta S_{\text{cold}} > 0$

Entropy of cold object **increases more** than entropy of hot object decreases  $\Rightarrow$  **net increase**

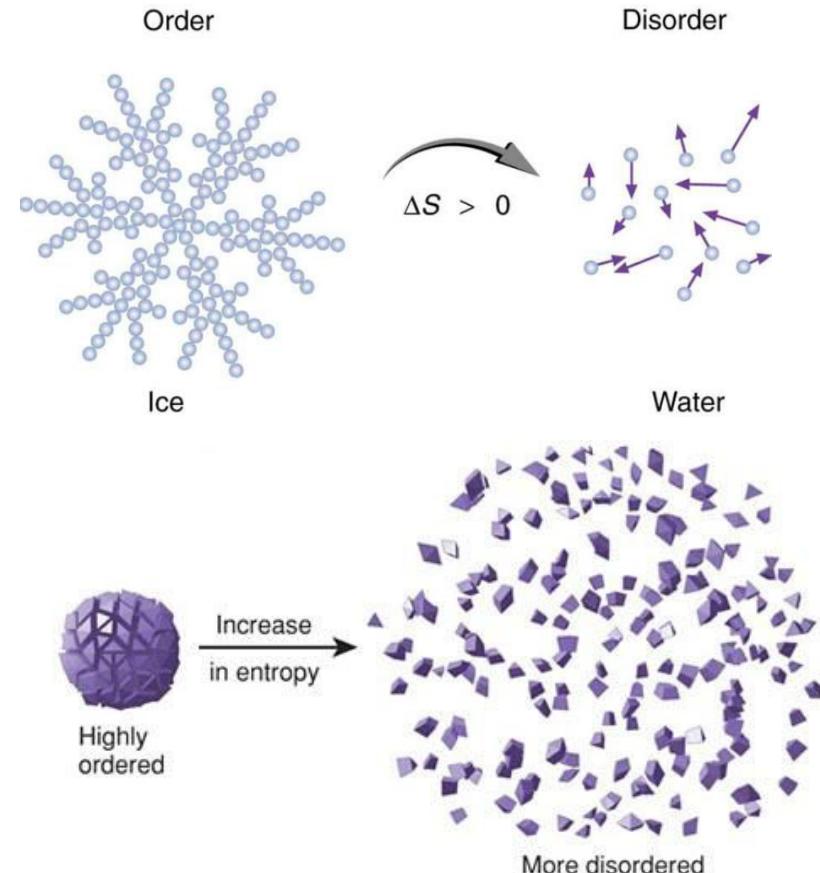
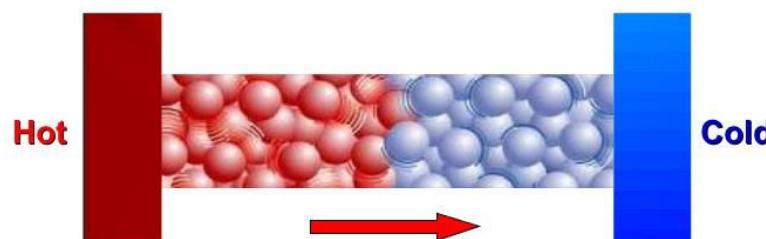
# Entropy

- Entropy was later understood much more deeply, at the *microscopic* level, by the great **Ludwig Boltzmann** (1844-1906), and summarized in his famous equation:  $S = k \log W$



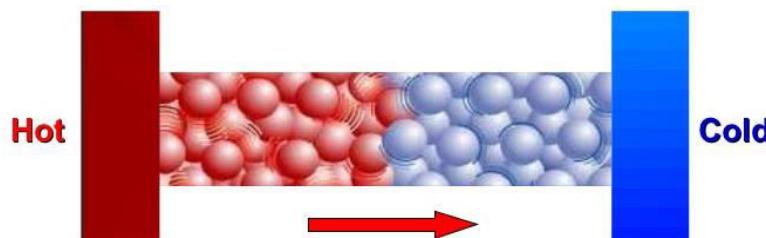
# Entropy

- $S = k \log W$
- This is one of the deepest insights we have into the nature of everyday reality.
- Before we explore it in more detail, let's appreciate it's profound generality:
  - ✓ Deals with spreading of thermal energy...
  - ✓ ...but also changes in **order**, or **complexity** (crucial for understanding life)

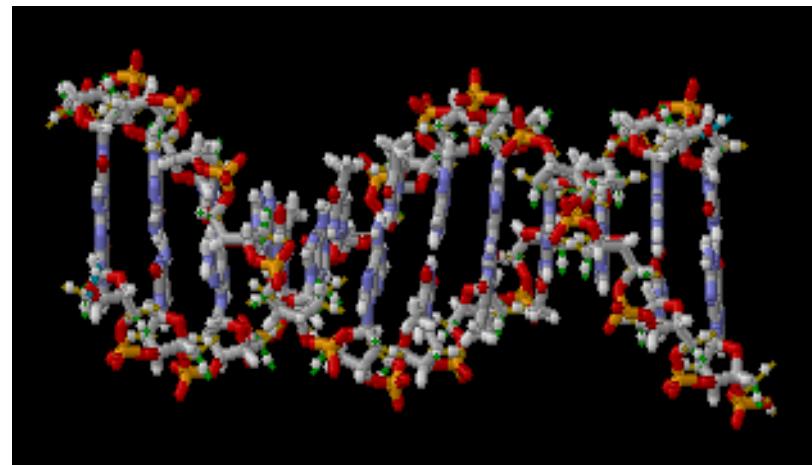


# Entropy

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Periodic to “aperiodic” crystals: lower order/complexity to higher order/complexity, or higher entropy to lower entropy

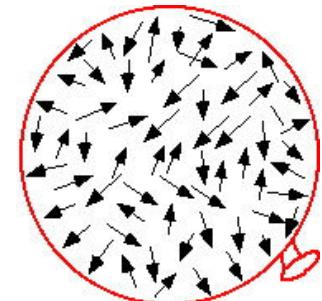


## Mathematics of Boltzmann's formula $S = k \log W$

- $S = k \log W$  is used to **quantify** the amount of disorder, or entropy ( $S$ ).
- $k$  is called **Boltzmann's constant**, and has units of **energy per degree of temperature**. This tells us entropy is intimately connected with the concepts of **energy** and **temperature**, as we shall see. For simplicity we will set  $k = 1$  (ignore this constant).
- $\log 100,000 = \log 10^5 = 5$ . The log function counts how many powers of 10 in a large number. It reduces stupendously large numbers like  $10^{100}$  (googol), often encountered in the statistics of natural systems, to more manageable numbers:  $\log 10^{100} = 100$ .
- The important quantity is  $W = \text{number of microstates compatible with a given macrostate}$ .

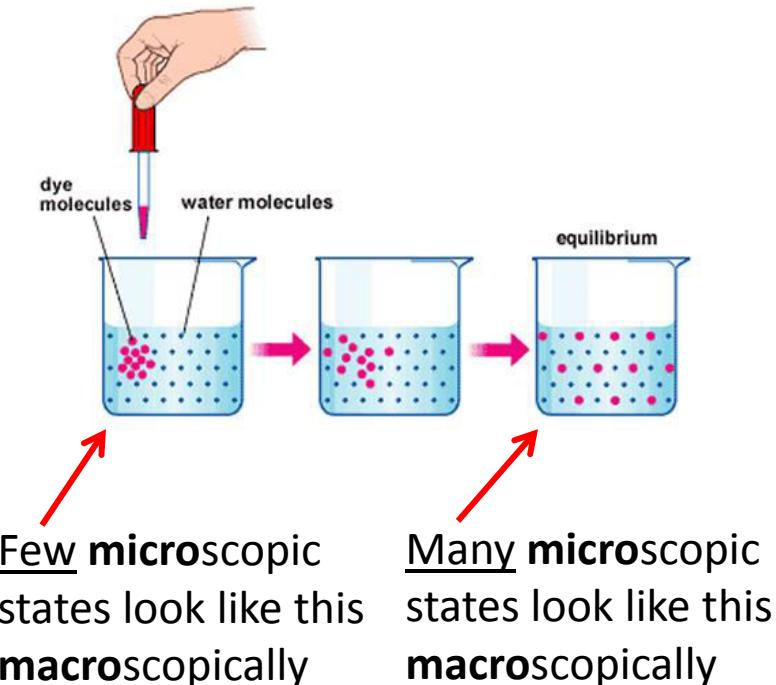
# Macrostates & Microstates

- The important quantity is  $W = \text{number of microstates compatible with a given macrostate}$ .
- E.g.: A balloon full of air:
  - **Macroscopic** description: Volume, pressure, temperature
  - **Microscopic** description: Position and velocity of every air molecule
  - $W$  is the stupendously large number of different possible **microscopic** states that would be *indistinguishable* (look the same to us) from a **macroscopic** point of view.



# Macrostates & Microstates

- The important quantity is  $W = \text{number of microstates compatible with a given macrostate}$ .
- E.g.: Diffusion of dye molecules:
  - Macroscopic** description: Less spread out, more spread out.
  - Microscopic** description: Position and velocity of every dye molecule.
  - As the blob of dye molecules spreads out, the number of distinct **microscopic** states that *look the same macroscopically*, which we call  $W$ , increases very (**exponentially**) rapidly.

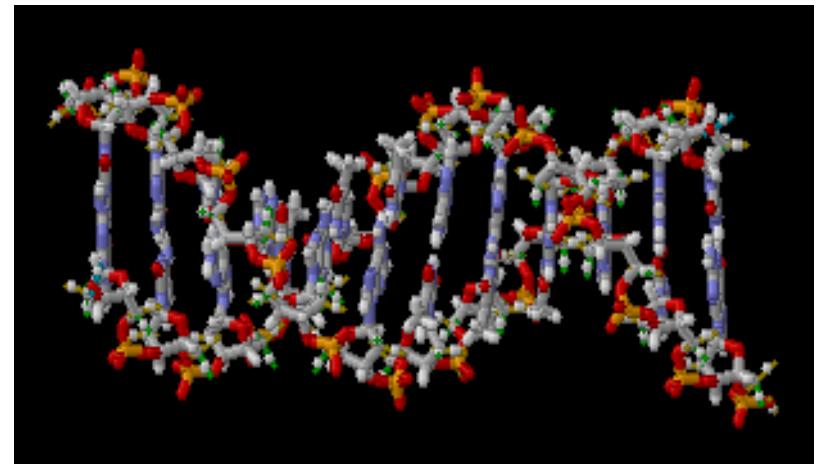


# Macrostates & Microstates

- “**Disorder**” is a vague word. The **precise** meaning of entropy is:  $S = k \log W$ .
- Entropy is a measure of **how many different ways** a set of particles can be rearranged (position and velocity), and **still look the same**.
- E.g.: DNA is a highly ordered arrangement of atoms. Almost any rearrangement will make the DNA look different. Small  $W \Rightarrow$  low entropy.
- E.g.: A rock crystal is **less** ordered in the sense that it is a repeating pattern of a **smaller set** of ordered atoms, which are interchangeable. Larger  $W \Rightarrow$  higher entropy.



Periodic to “aperiodic” crystals: lower order/complexity to higher order/complexity, or higher entropy to lower entropy



# Macrostates & Microstates

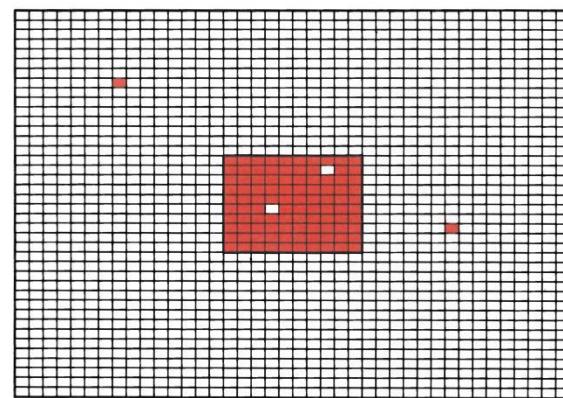
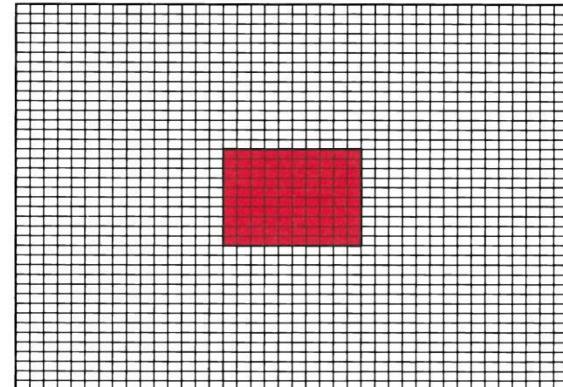
$S = k \log W$  is a powerful **bridge**  
between the **macro** and **micro** worlds.



# Example of $S = k \log W$ in action

Consider a simple **model universe** (Atkins—*The Second Law*):

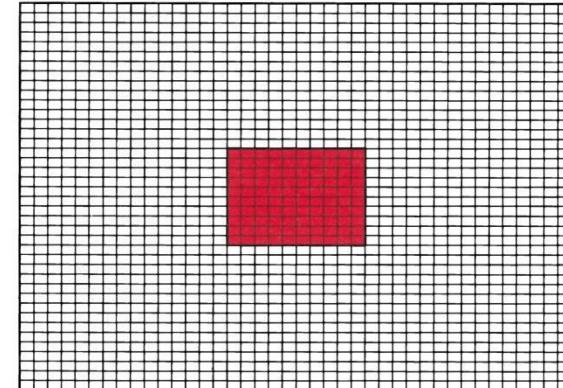
- Universe =  $40 \times 40 = 1600$  atoms
- System =  $10 \times 10 = 100$  atoms
- Environment =  $1600 - 100 = 1500$  atoms
- Atoms have either **one** unit of energy (red) or **no** energy (white)
- Universe starts with:
  - ✓ 100 units of energy in the system (all of its atoms “ON”)
  - ✓ No energy in the environment (all of its atoms “OFF”)
- Thermal motion of “ON” atoms jiggle neighboring atoms, transferring their energy: energy *naturally* disperses/diffuses
- But energy is **conserved**: total number of “ON” atoms = 100



# Example of $S = k \log W$ in action

Initial entropy:

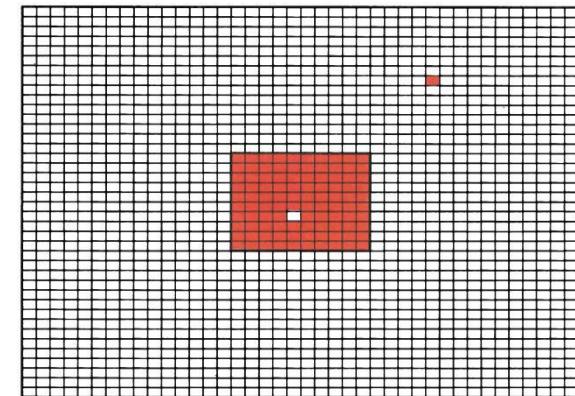
- There is only **one** way all the energy can be in the system, and none in the environment. Thus:  $W = 1 = 10^0$
- Thus:  $S = \log W = \log 10^0 = 0$ . This is the state of lowest possible entropy of the universe
- Minimum entropy = minimum disorder = maximum order
- From here on, the universe inexorably ratchets itself towards higher and higher entropy, as it sinks further and further into disorder and chaos...



# Example of $S = k \log W$ in action

One unit of energy diffuses from the system into the environment:

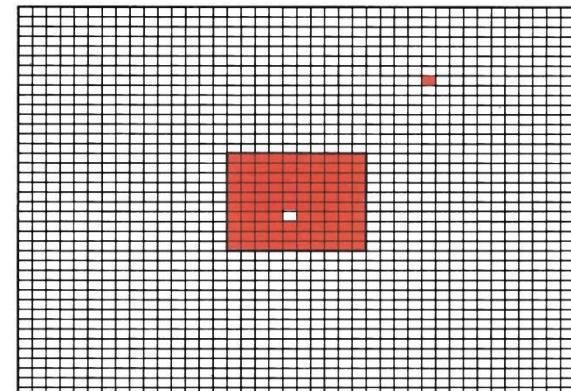
- **Temperature** is a measure of the **average** thermal energy per atom. Thus:
  - ✓ The temperature of the **system decreases**, and that of the **environment increases**, like the cooling cup of coffee warming the air in the room
  - ✓ The universe has taken the first step towards **thermodynamic equilibrium**: system and environment at the **same temperature**
- Each different possible location of the single “ON” atom is a different **microstate** of the environment, but all of these microstates correspond to the **same macrostate** of the environment (same **average** thermal energy, or **temperature**). Similarly for the location of the single “OFF” atom in the system



# Example of $S = k \log W$ in action

One unit of energy diffuses from the system into the environment:

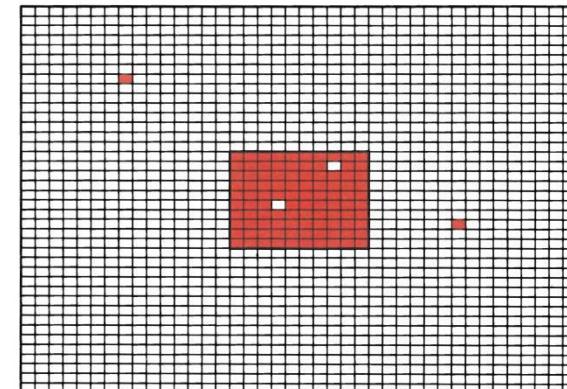
- The number of different ways **one “ON”** can be distributed in the **environment** (environment microstates) is 1500
- The number of different ways 99 “ONs” (or **one “OFF”**) can be distributed in the **system** (system microstates) is 100
- The number of different ways **both** can happen (the number of distinct universe **microstates** compatible with this universe **macrostate**) is  $W = 1500 \times 100 = 150,000 = 10^{5.2}$
- Entropy of the universe **increases** from 0 to  $\log 10^{5.2} = 5.2$
- The flow of energy from hot to cold (the “lawless” dispersion of energy) has increased the disorder of the universe



## Example of $S = k \log W$ in action

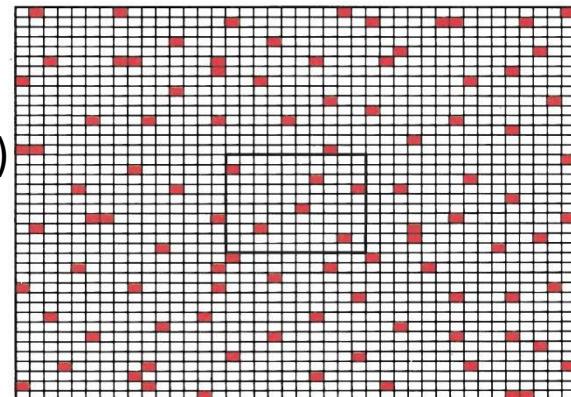
Two units of energy diffuse from the system into the environment:

- The number of different ways **two “ONs”** can be distributed in the **environment** is  $1500 \times 1499 \div 2 = 1,124,250$
- The number of different ways 98 “ONs” (or **two “OFFs”**) can be distributed in the **system** is  $100 \times 99 \div 2 = 4950$
- The number of different ways **both** can happen is  $W = 1,124,250 \times 4950 = 5,565,037,500 = 10^{9.7}$
- Entropy of the universe **increases** from 5.2 to  $\log 10^{9.7} = 9.7$
- The flow of energy from hot to cold (the “lawless” dispersion of energy) continues to increase the disorder of the universe



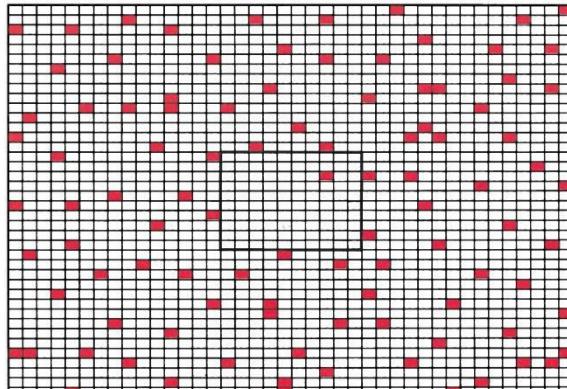
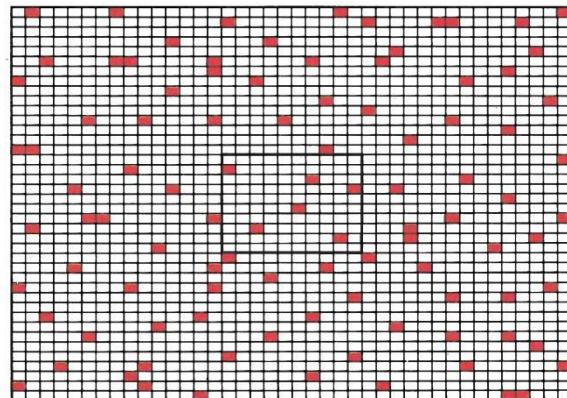
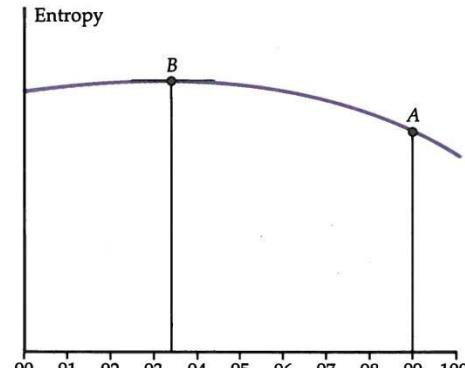
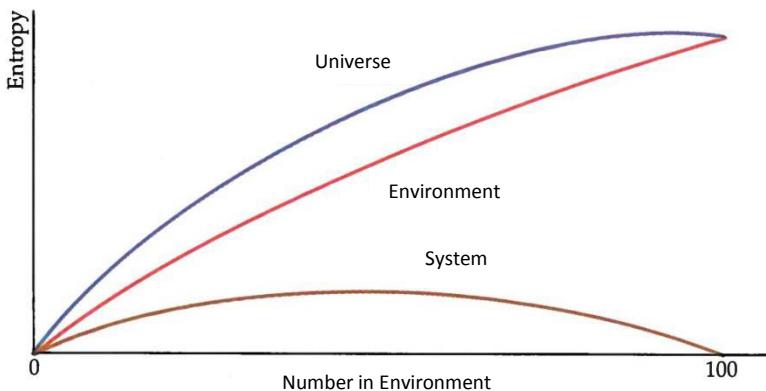
## Example of $S = k \log W$ in action

- This “**lawless**” diffusion of energy continues until **thermal equilibrium** is reached, i.e., the system and environment reach the **same temperature** (same **average** thermal energy per atom)
- E.g., the cup of coffee has cooled, and the room air has warmed up, such that they are now at the **same temperature**
- In this example, **thermal equilibrium** corresponds to 6 or 7 “ONs” in the system, and 93 or 94 “ONs” in the environment, i.e., the **average** number of “ONs” is the **same** in both regions



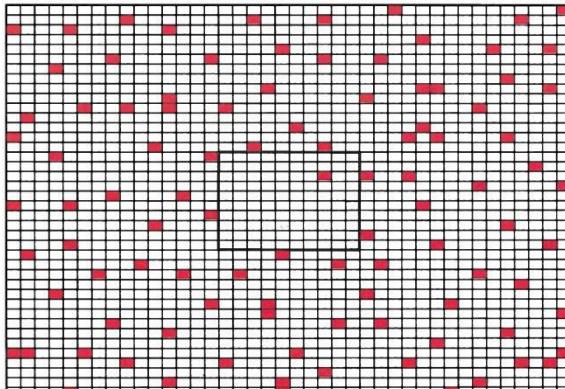
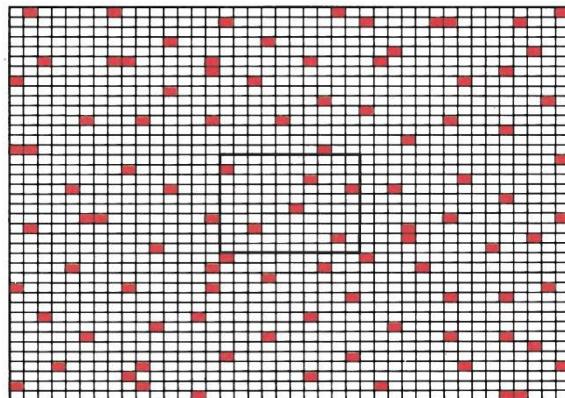
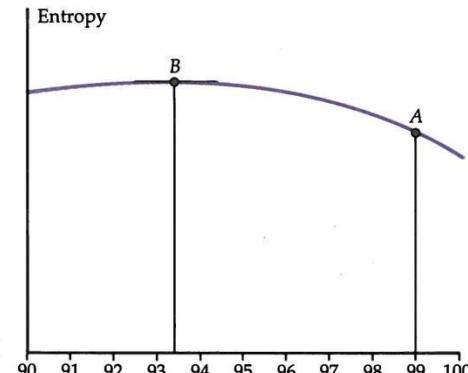
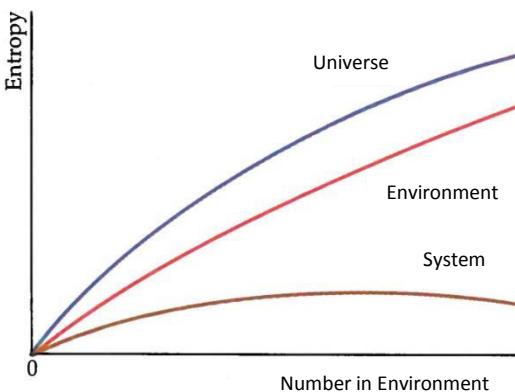
# Example of $S = k \log W$ in action

- **Thermal equilibrium** is also the point of **maximum entropy**
- If **more** energy diffuses into the environment (more than 93 or 94), it leaves **fewer** “ONs” in the system. This has two effects:
  - ✓ While it **increases** the entropy of the environment, it **decreases** the entropy of the system **more** (because there are now so few “ONs” in the system), such that the **total** entropy (entropy of the universe) actually **decreases**



# Example of $S = k \log W$ in action

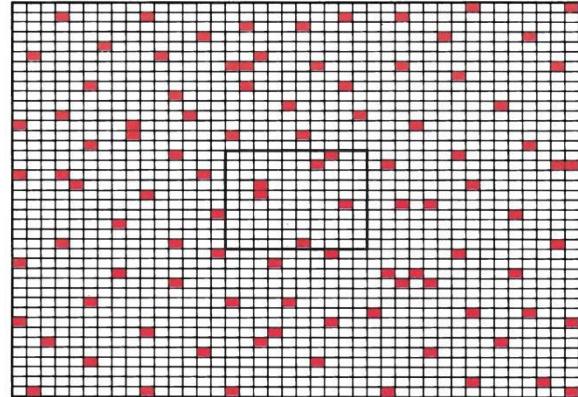
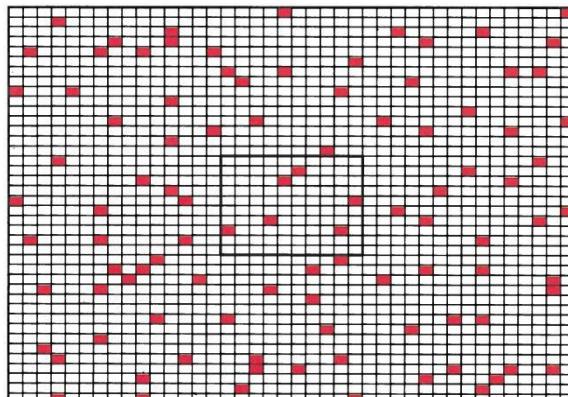
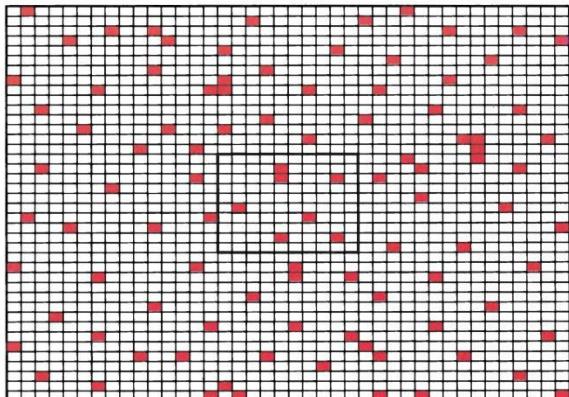
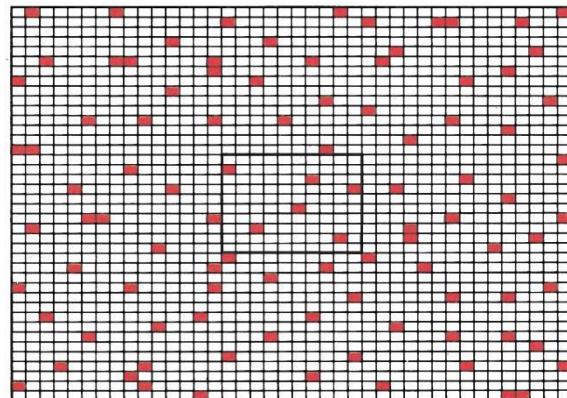
- **Thermal equilibrium** is also the point of **maximum entropy**
- If **more** energy diffuses into the environment (more than 93 or 94), it leaves **fewer** “ONs” in the system. This has two effects:
  - ✓ The system gets **colder** than the environment, and so thermal energy would naturally flow **back** into the system, **restoring** thermal equilibrium and maximum entropy



## Example of $S = k \log W$ in action

- Two additional points:

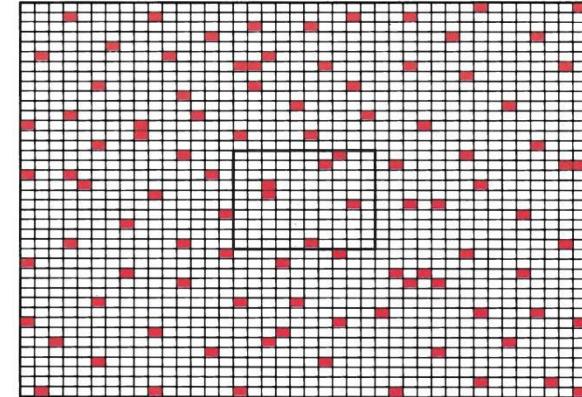
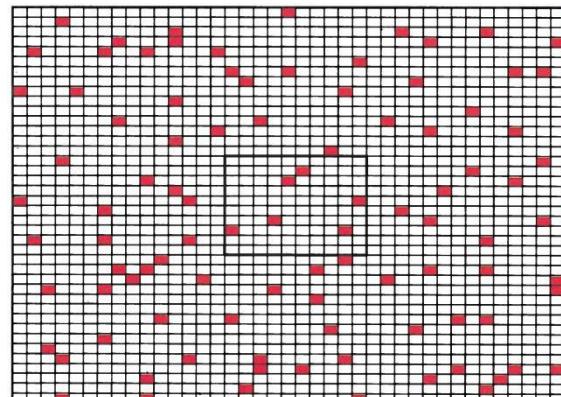
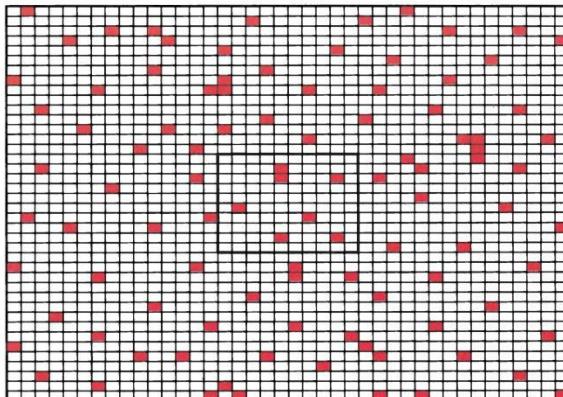
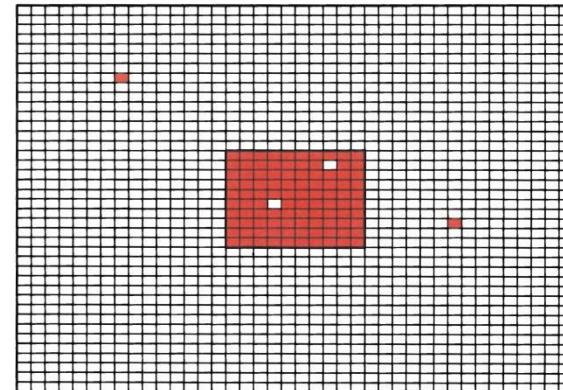
✓ This is a **dynamic** equilibrium. Thermal energy **continues** to flow randomly between the system and the environment, and between atoms within the system and atoms within the environment, but there no **net** flow. The **average** energy per atom in the universe remains constant



# Example of $S = k \log W$ in action

- Two additional points:

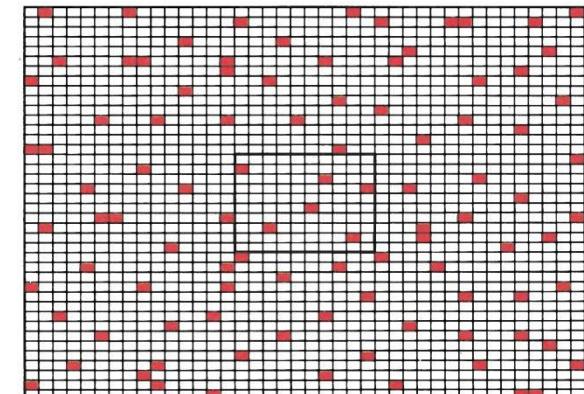
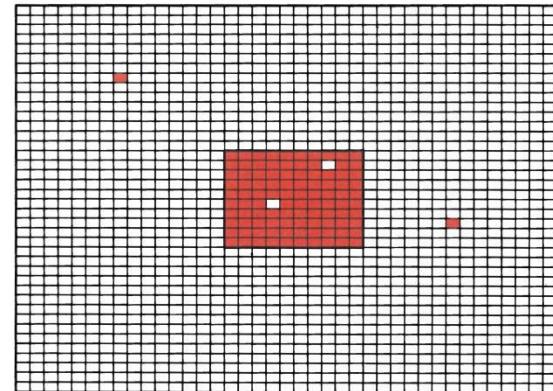
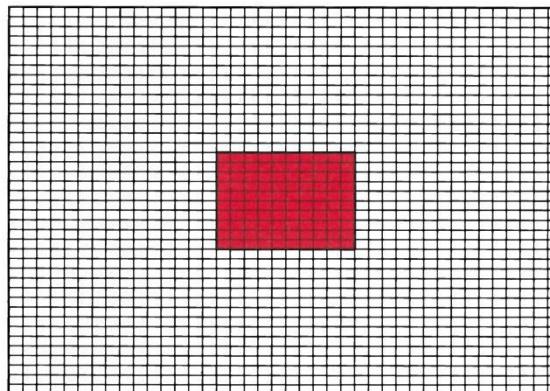
✓ There are **stupendously** more microstates in the **thermal equilibrium (maximum entropy)** macrostate, compared to any other non-equilibrium macrostate. There's no reason the universe can't return to a non-equilibrium macrostate, it's just **stupendously unlikely**. The process is effectively **irreversible**—the universe gets “locked out of the past”



# Summary

“Energy tends to disperse”  $\Rightarrow$  “Entropy tends to increase”

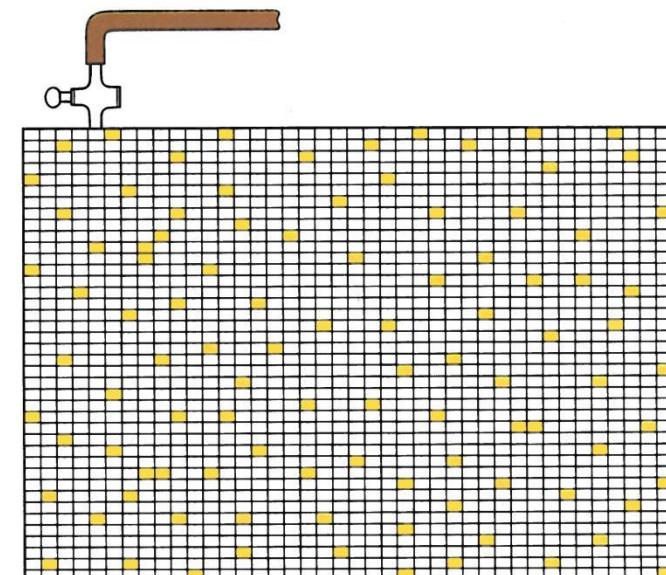
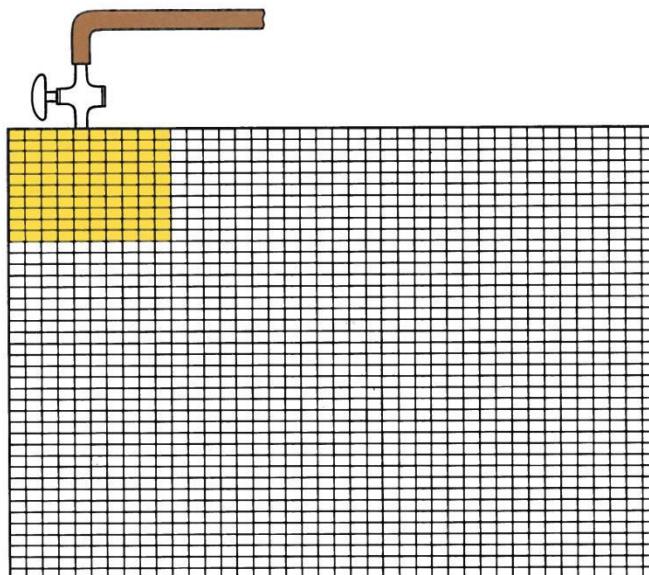
What *drives* the dispersal is **random/purposeless** thermal motion



Other ways entropy can increase...

When **particles** disperse, entropy also increases.

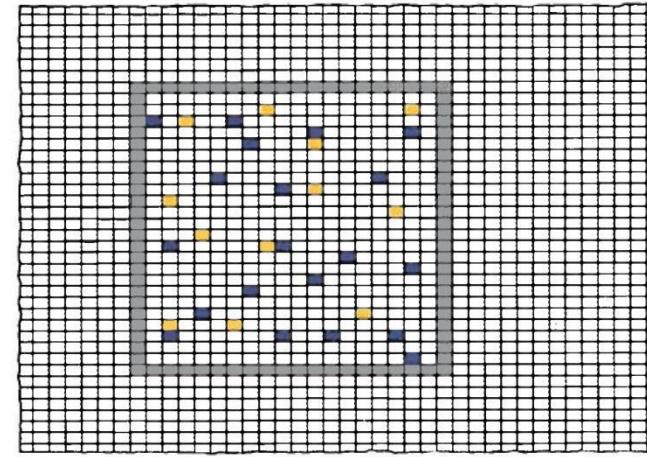
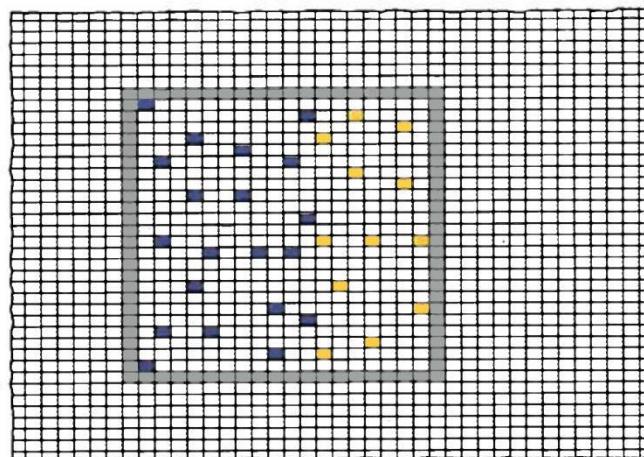
(There are **stupendously** more ways for particles to uniformly fill a volume, than to occupy one corner:  $S = k \log W$  applies here too!)



Other ways entropy can increase...

When particles of different type **mix**, entropy also increases.

(There are **stupendously** more ways for particles of different type to be mixed, than remain separated:  $S = k \log W$  applies here too!)

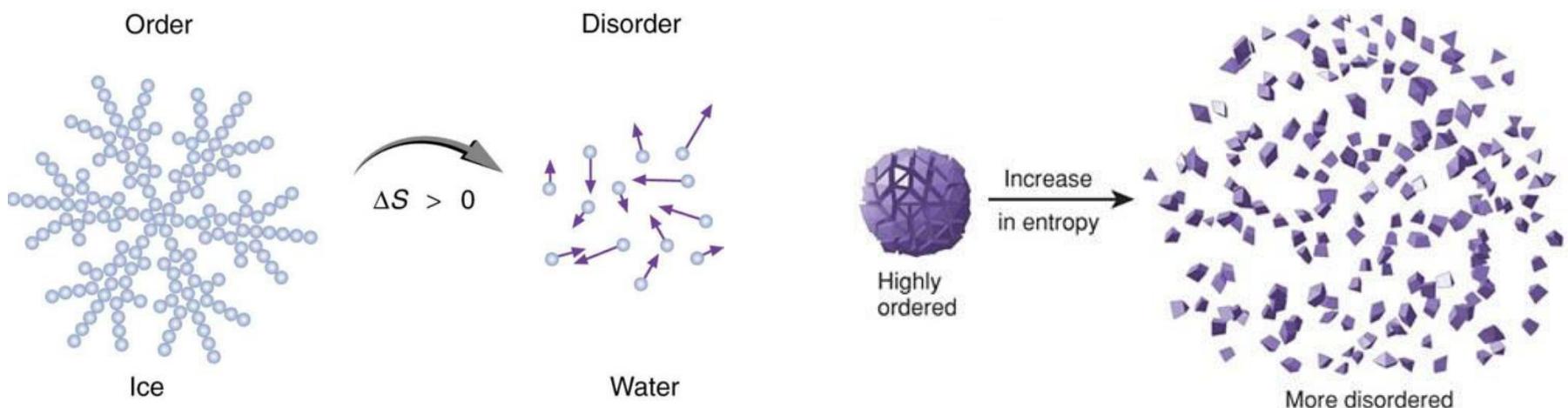
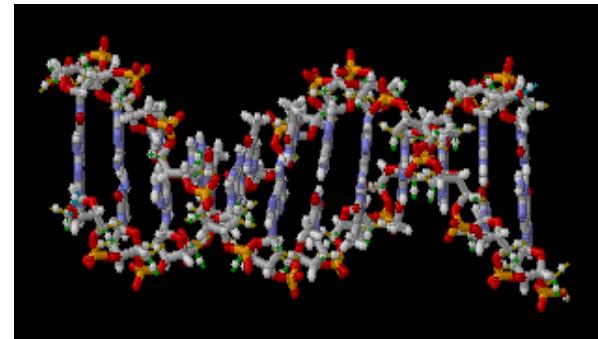


## Other ways entropy can increase...

When **structural order** decreases, entropy also increases.

Conversely, when **structural order increases**, entropy *decreases*.

(There are **stupendously** more ways for particles to be structurally disordered than ordered:  $S = k \log W$  applies here too!)



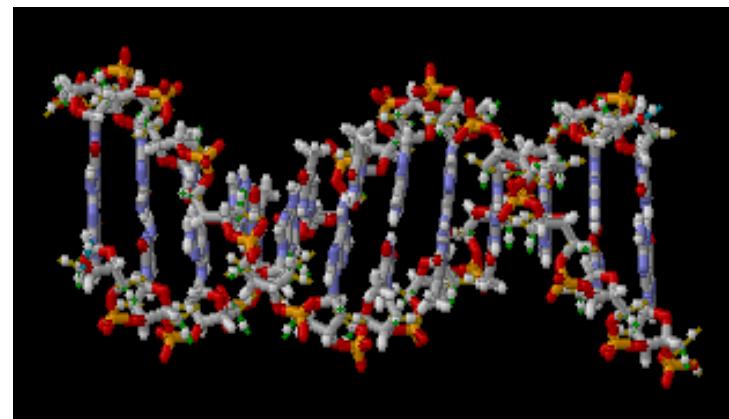
## Summary

- Boltzmann's formula [ $S = k \log W$ ] *quantitatively* enumerates disorder in **all** of its forms. The **universality** of this connection between the **macroscopic** and **microscopic** worlds is why this formula is so important and far-reaching.
- The second law of thermodynamics [ $\Delta S \geq 0$ ] is **also universal**, at least in the “law of large numbers” sense. It determines the **direction of spontaneous change** for **all processes** in nature: ***all*** change is driven by the purposeless/lawless spreading of energy and particles.

**So what?**

# Life and the Second Law

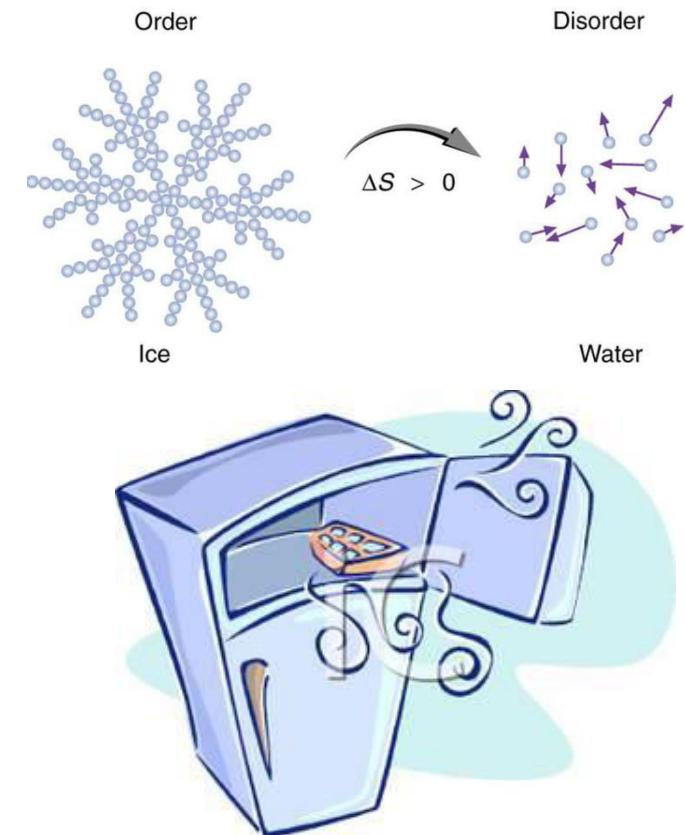
- Living organisms exhibit a very high degree of **order** or **complexity**, relative to the surrounding matter.
- How do they **maintain** this order against the tendency towards universal decay into disorder? *Doesn't life violate the Second Law?*
- What about **evolution** (to organisms of ever higher order or complexity)? Surely *it* violates the Second Law!?
- **No:** The universal ratcheting towards disorder is only **on balance**. Entropy can **decrease** in one location, as long as it **increases more** somewhere else, such that the **total** entropy increases (or stays the same).



Let's look at a simple example of entropy decreasing *locally*, but increasing globally.

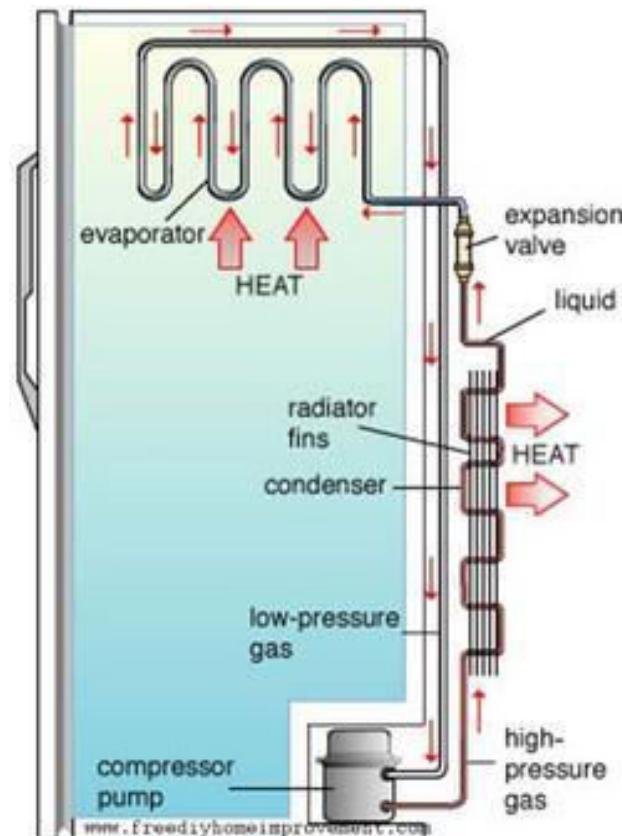
# Life and the Second Law

- A **freezer** can convert water (at 0°C) to ice (at 0°C).
- Ice is a **more ordered** structure than water, so changing water to ice **reduces** the entropy of the H<sub>2</sub>O.
- The water-to-ice transition **releases** energy (“latent heat”) because H<sub>2</sub>O bonds in ice are more stable (**stronger/lower energy**) than H<sub>2</sub>O bonds in water.
- The freezer **removes** this energy and **dumps** it into the environment (outside air). The resulting entropy **increase** (energy spreading) **exceeds** the water-to-ice entropy decrease  $\Rightarrow$  **net entropy increase**.
- A freezer **does not** violate the Second Law.



# Life and the Second Law

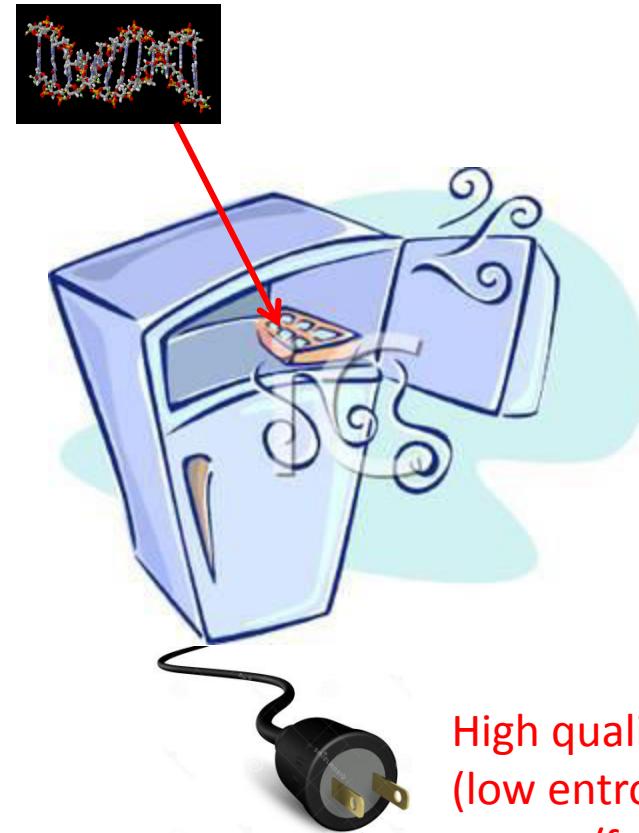
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- The freezer **removes** this energy and **dumps** it into the environment (outside air). The resulting entropy **increase** (energy spreading) **exceeds** the water-to-ice entropy decrease ⇒ **net entropy increase**.
- A freezer **does not** violate the Second Law.



# Life and the Second Law



=



High quality  
(low entropy)  
energy/food in

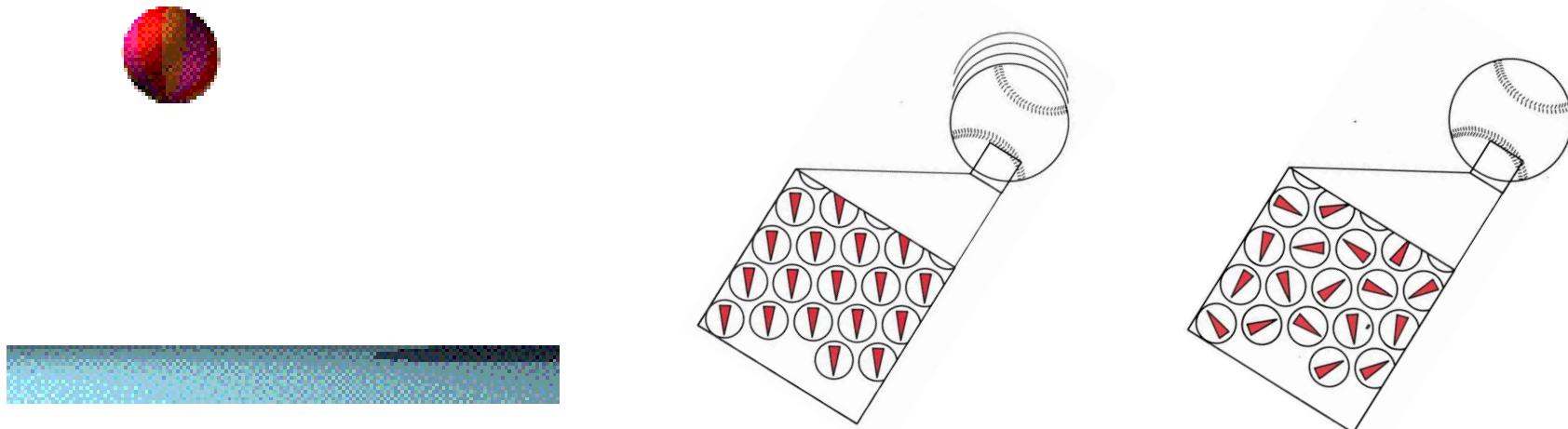
- A frog **does not** violate the Second Law.

## Order from Disorder

- Let's look at another simple example of entropy decreasing *locally*, but increasing globally:
  - ✓ ...but now in much more detail, to see how it actually works
  - ✓ ...how a **complex machine** can **harness** the spontaneous, purposeless dispersal of energy to **create order locally**, at the expense of creating more disorder globally
  - ✓ ...**local** order from the **global** flow to disorder, or “order from disorder”, for short
  - ✓ ...this is a central theme to understanding what life is

# Order from Disorder

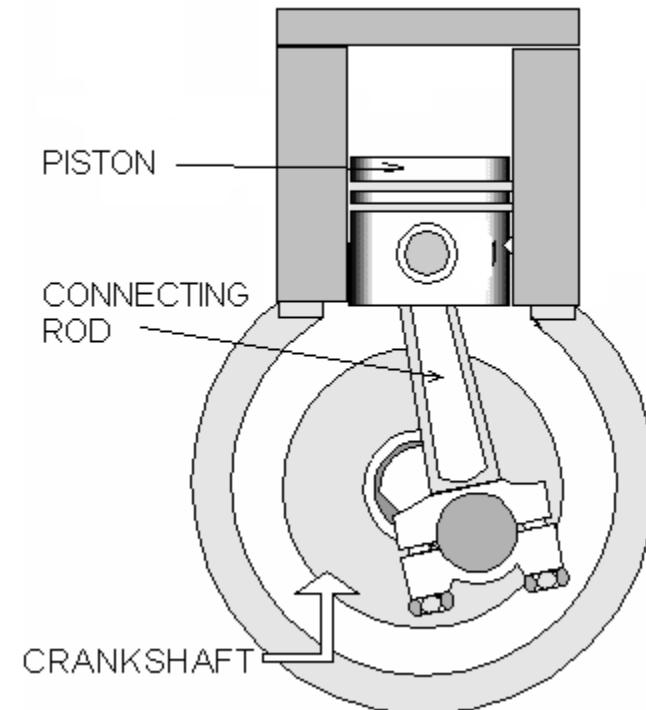
- First, let's recall the natural flow from order to disorder:



- **But reversing this process is more difficult:** Given a ball in the state on the right, at rest on the ground, it is possible, but **stupendously** unlikely, that the incoherent (disordered) kinetic energy of its atoms will spontaneously become coherent (ordered), with all the motions aligned upwards, resulting in the ball jumping up off the ground!

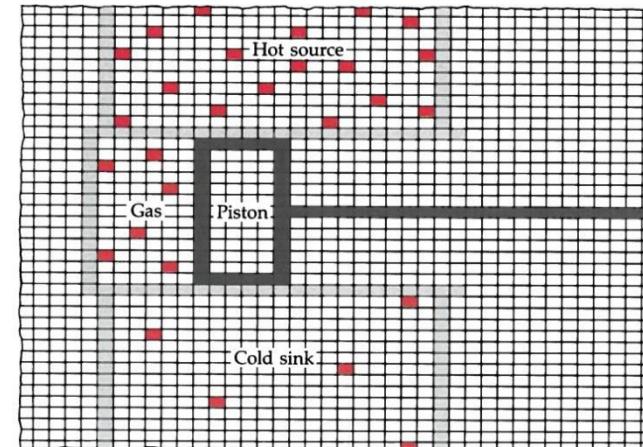
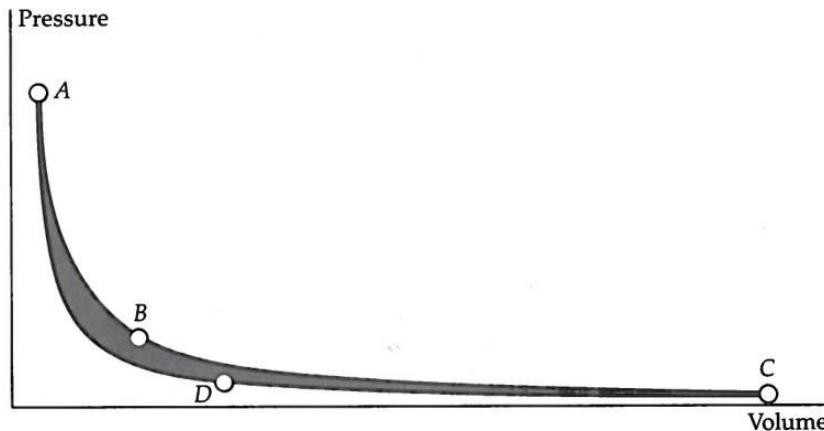
# Order from Disorder

- Nevertheless, machines exist all around us that **spontaneously** create **order** from **disorder**



# Order from Disorder

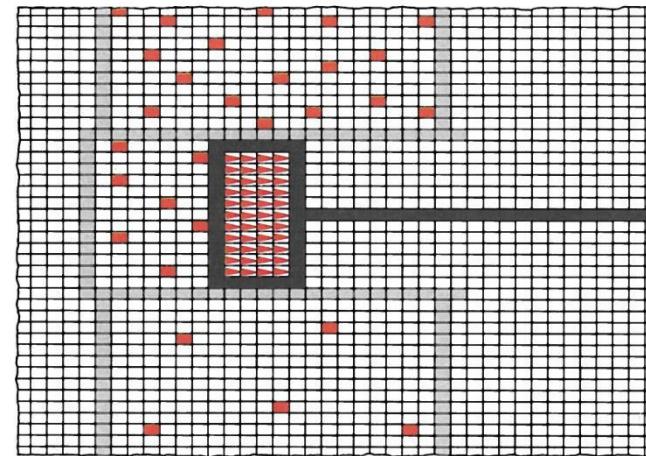
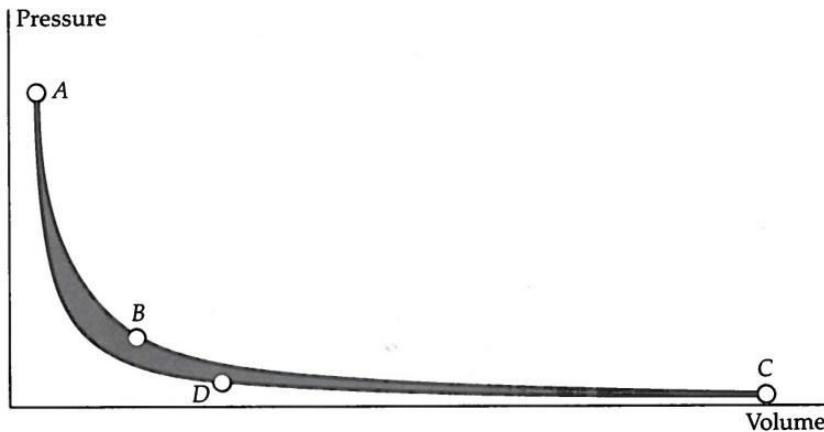
- Nevertheless, machines exist all around us that **spontaneously** create order from disorder



- Above is a simpler version of a car engine that works on what's called “Carnot cycle”
- A fixed amount of gas is contained in a cylinder with a moveable piston
- The gas can be alternately brought into contact with the “hot source” or the “cold sink”

# Order from Disorder

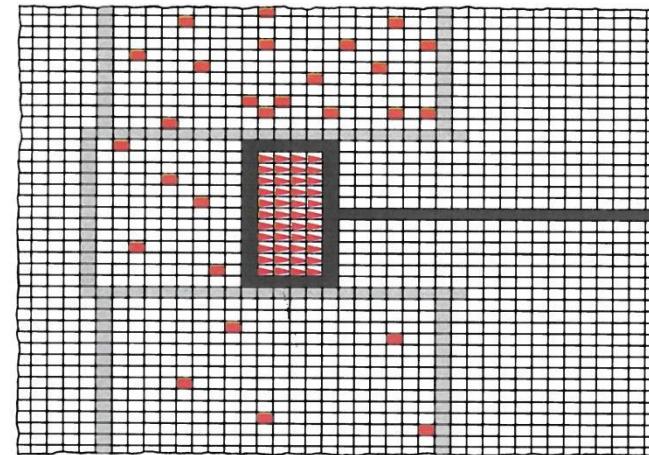
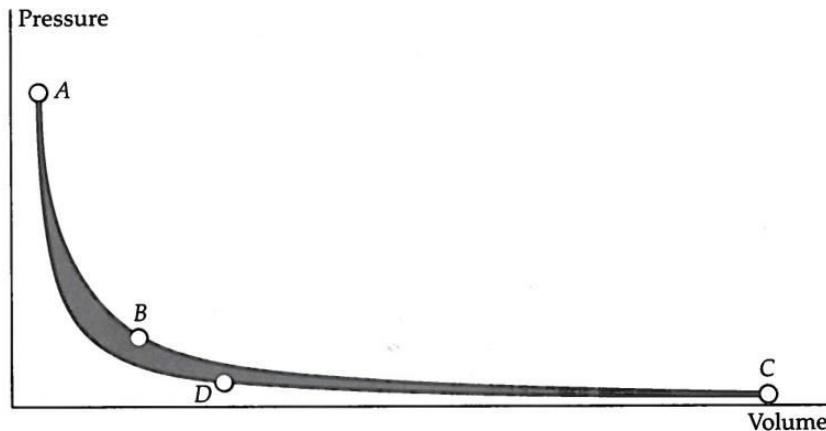
- Nevertheless, machines exist all around us that **spontaneously** create order from disorder



- **A-B:** The gas is in contact with the “hot source”, and remains at the same temperature
- Hot gas atoms bombard the piston, which absorbs **only right-moving KE (this is the key)**. **Disordered KE is converted into ordered KE!** As the atoms turn “OFF”, fresh disordered KE *spontaneously* flows in from the “hot source”, maintaining the temperature of the gas as the piston moves to the right

# Order from Disorder

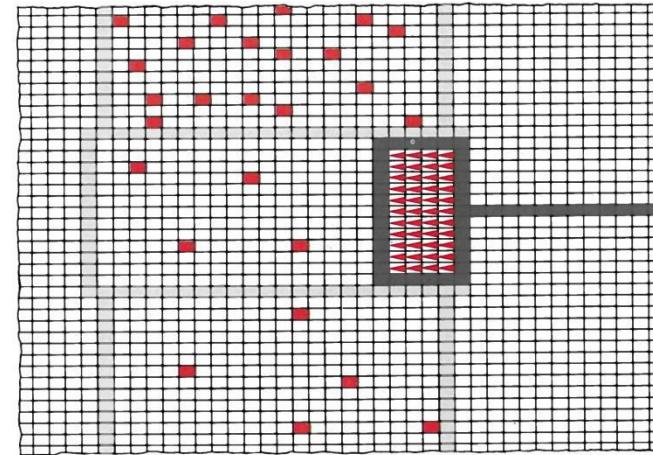
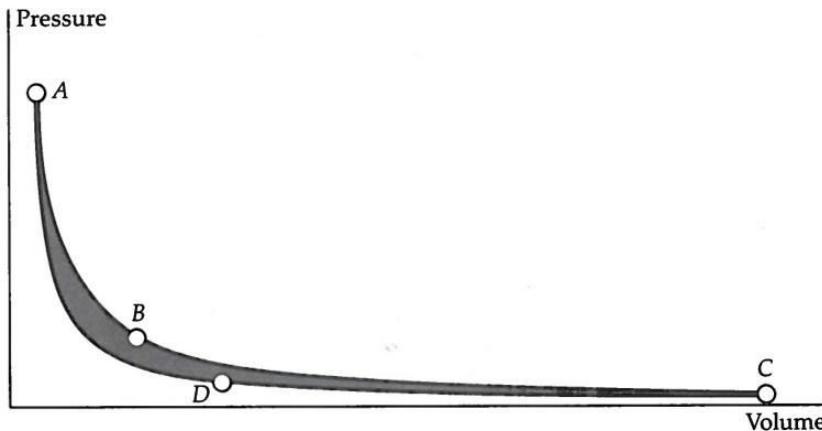
- Nevertheless, machines exist all around us that **spontaneously** create order from disorder



- **B-C:** The gas is isolated from the “hot source”, and cools as it continues to expand
- Hot gas atoms continue to bombard the piston, but as their disordered KE is converted into the piston’s ordered KE (gas atoms turn “OFF”), no fresh KE flows in from the “hot source”, causing the gas to cool as it expands (and the piston moves further to the right)

# Order from Disorder

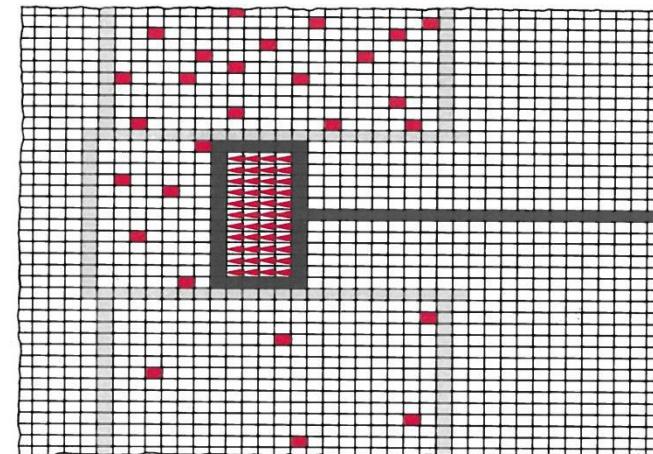
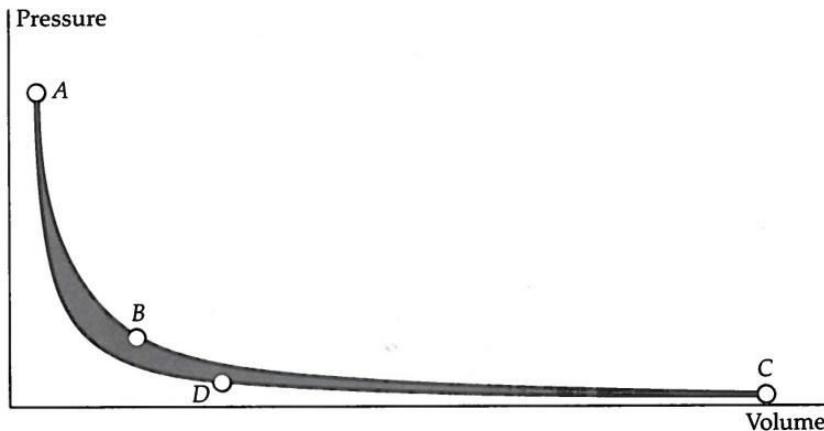
- Nevertheless, machines exist all around us that **spontaneously** create order from disorder



- **C-D:** The gas is put in contact with the “cold sink”, and remains at the same temperature
- The piston turns around and is now moving left, hitting the cold gas atoms, transferring to them ordered KE, which is quickly randomized by collisions into disordered KE. This would normally heat up the gas (turning more atoms “ON”), but the extra thermal energy *spontaneously* flows into the cold sink as the piston continues to move to the left

# Order from Disorder

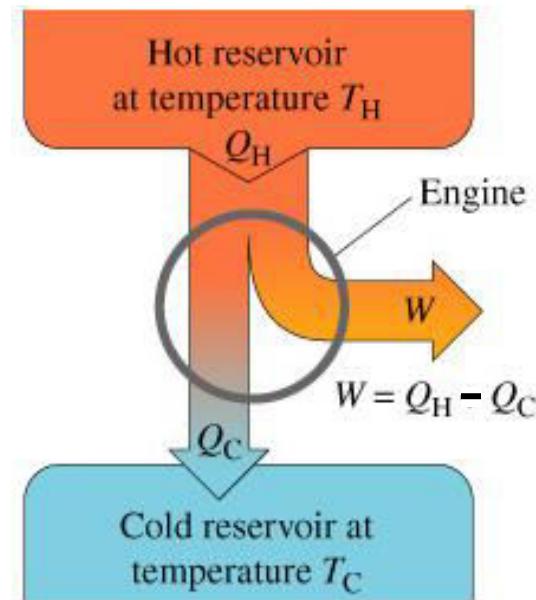
- Nevertheless, machines exist all around us that **spontaneously** create **order** from **disorder**



- **D-A:** The gas is isolated from the “cold sink”, and heats up as it is compressed
- The piston continues moving left, hitting the now warmer gas atoms, transferring to them additional ordered KE, which is quickly randomized by collisions into disordered KE. Because the extra thermal energy is not drawn off, the gas heats up (more atoms turn “ON”). This brings us back to **A**, the starting point of the cycle. The cycle then repeats.

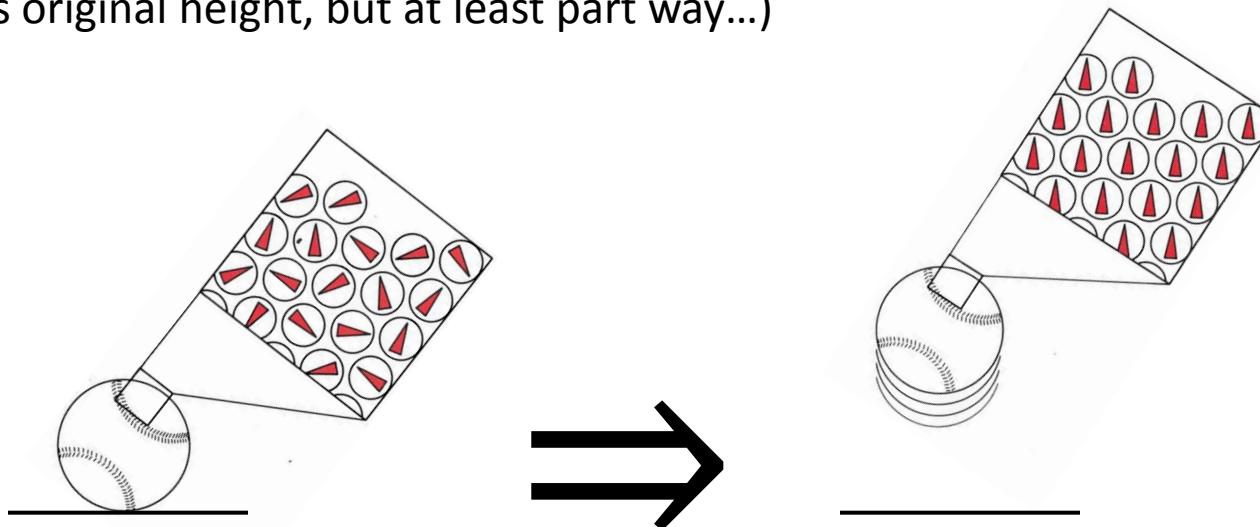
# Order from Disorder

- Nevertheless, machines exist all around us that **spontaneously** create **order** from **disorder**
- Over one complete cycle:
  - ✓ **Disordered KE** (thermal energy) **spontaneously** flows from the hot source into the gas in the cylinder ( $Q_H$ ), and from this gas into the cold sink ( $Q_C$ )
  - ✓ In the process, **ordered KE** in the form of the motion of the piston was extracted to do useful “work” ( $W$ ), e.g., make the car move (coherent KE)
  - ✓ In short: **Order from spontaneous flow to disorder!**
  - ✓ **Note:** Not all of  $Q_H$  is converted to useful  $W$ . A “waste heat”  $Q_C$  is necessary to ensure **net entropy increase** (this will be important later in idea of “free energy”)



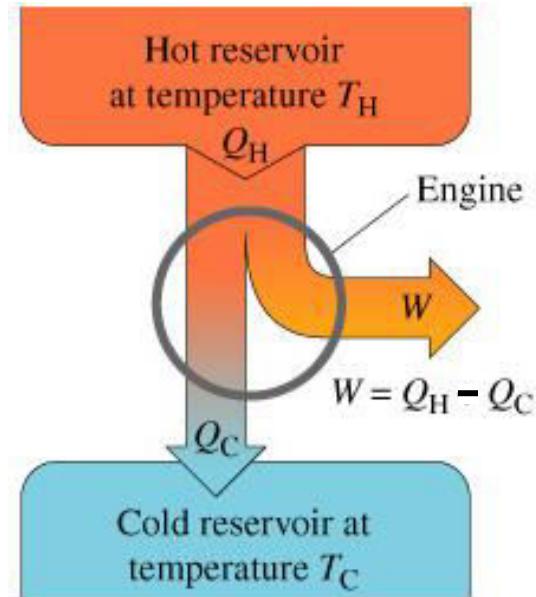
## Order from Disorder

- Nevertheless, machines exist all around us that **spontaneously** create **order** from **disorder**
- Effectively, we have made the ball **spontaneously jump up!**  
(Not to its original height, but at least part way...)



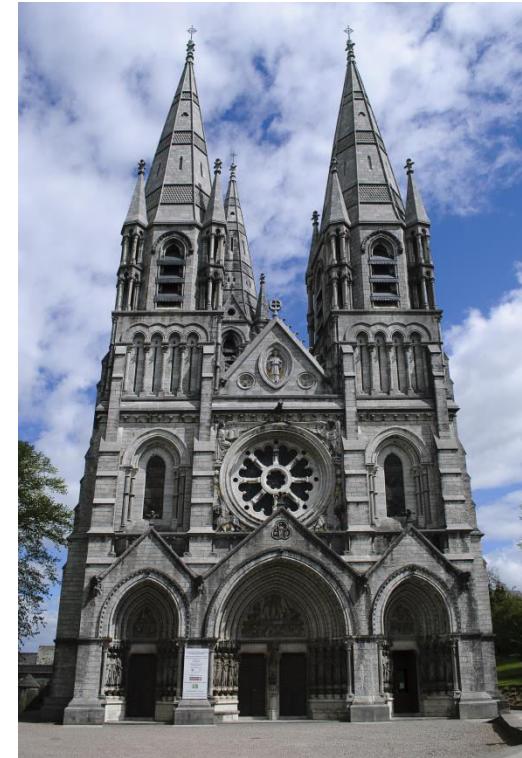
# Order from Disorder

- Nevertheless, machines exist all around us that **spontaneously** create order from disorder
- Thinking in terms of **entropy**:
  - ✓ In an **ideal** engine,  $\Delta S = 0$ :
    - $\Delta S_H = -Q_H/T_H < 0$  (entropy of hot source decreases)
    - $\Delta S_C = Q_C/T_C > 0$  (entropy of cold sink increases)
    - Ratios of temperatures and energy flows are such that:  
 $\Delta S = \Delta S_H + \Delta S_C = 0$ , just consistent with 2<sup>nd</sup> Law,  $\Delta S \geq 0$ .
    - But an **ideal** engine runs **infinitely slowly** (quasi-static). To extract ordered energy at a **finite rate**, we need  $\Delta S > 0$ .
  - ✓ The engine “harnesses” the spontaneous flow of thermal energy (disordered, incoherent KE) from hot to cold to **spontaneously** extract ordered, coherent KE



# Order from Disorder

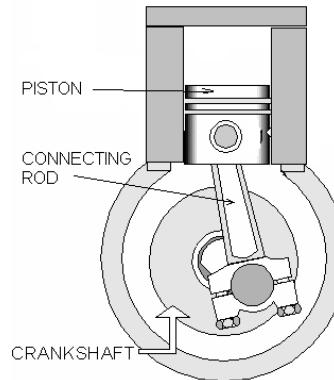
- Nevertheless, machines exist all around us that **spontaneously** create **order** from **disorder**
- Thinking in the **big picture**:
  - ✓ This coherent KE can be used to **move people** (cars, planes), **build structures** (bridges, cathedrals), and do myriad other constructive things. The universe's inexorable slide into chaos can be **harnessed** for **construction** of order, as long as it is accompanied by **greater destruction** of order elsewhere
  - ✓ But it requires a **complex machine**. Early on, humans mastered burning fuels to **produce heat** (wood, coal, oil—trapped energy from the Sun; then uranium for fission—energy from other stars; soon hydrogen for fusion—energy from the Big Bang). But, aside from feeding fuel to animals and slaves, we only recently figured out how to burn fuels to **produce work**. This sparked the industrial revolution.



**So what?**

# Order from Disorder

- Think about this: A human is (at least) just such a complex machine:
  - It takes in low entropy material containing high quality energy: food-fuel
  - It “burns” this food-fuel and expels waste high entropy material / low quality energy: excrement / body heat
  - In the process, it constructs low entropy materials (DNA, cells, etc.) and extracts highly ordered energy for locomotion, consciousness, etc.

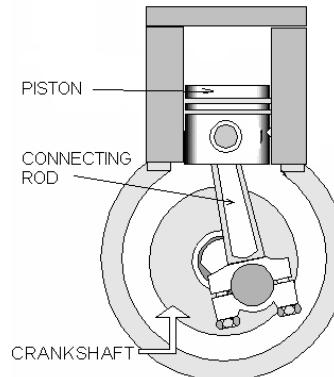


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# Order from Disorder

- Think about this: A human is (at least) just such a complex machine:
  - Once you have the machine, you just need to “feed” it, and it will function spontaneously
  - What animates living organisms is simply the spontaneous, purposeless, dispersion of energy (& particles) from more ordered to less ordered forms
  - A human is a machine that harnesses the inexorable ratcheting of the universe towards higher entropy to maintain its relatively low entropy form

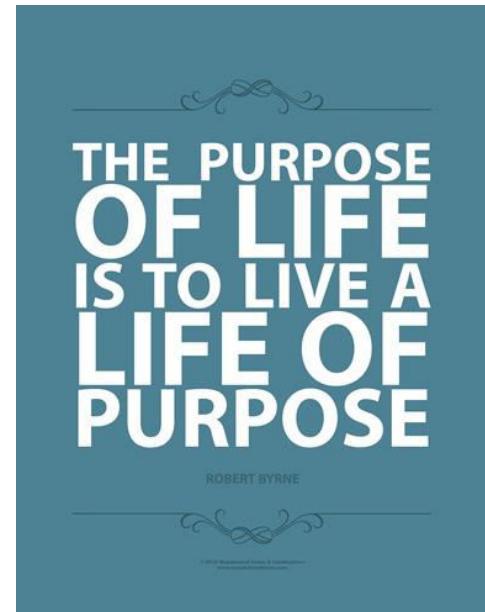


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# Order from Disorder

- Questions:
  - You're joking, right? Show me **how** a living organism is **essentially identical** to a piston engine!
  - Okay, maybe I'm convinced, but how could a machine as complex as a human **spontaneously** arise ***in the first place!***
  - Nature **spontaneously** creates ordered structures like snowflakes. If I'm just a "snowflake," what does this say about the "**purpose**" of life? Am I a "*special* snowflake"?



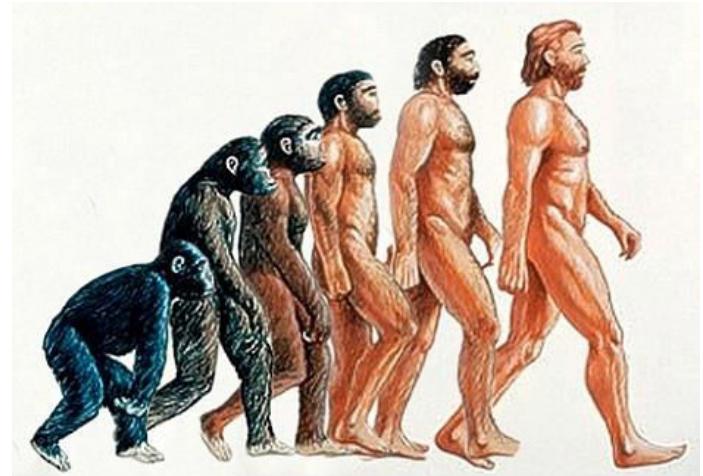
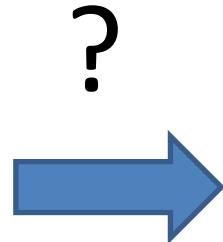
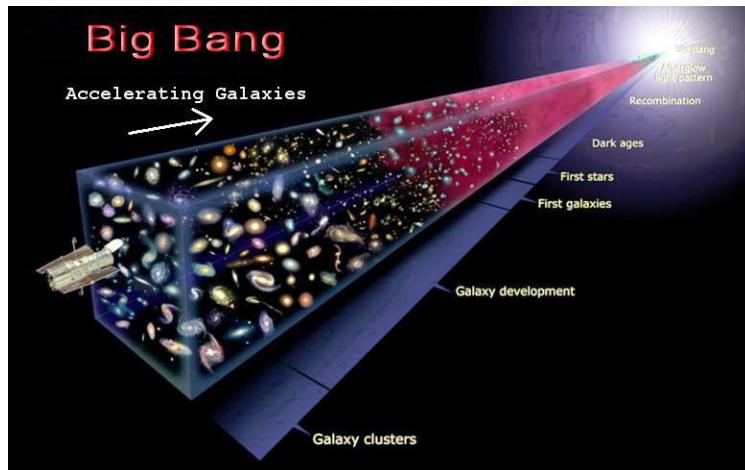
- ✓ Thinking about life in the context of basic physics provides a thought-provoking perspective. In general, that's what science does: it **challenges** our thinking.
- ✓ Considering that physics is the most “fundamental” of the sciences (in that it deals with the most elemental aspects of nature: space, time, energy, etc.), is this perspective saying something **fundamental** about the nature of life?
- ✓ ...or is it merely one of many, **equally fundamental** perspectives from other disciplines: biology, chemistry, fine arts, literature, theology, etc. Surely, **all perspectives** enrich our understanding of what life “really” is!

# Natural order from disorder?

Can nature **spontaneously** create order/complexity?

# Natural order from disorder?

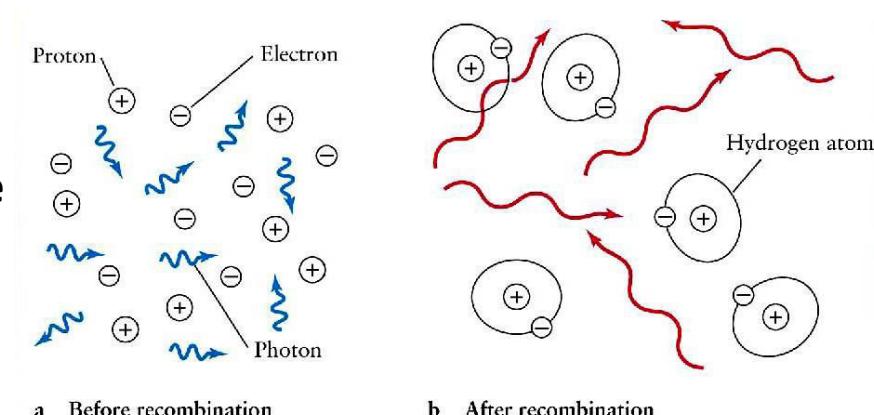
Obviously, YES. The entire history of the universe is FILLED with precisely this process.



# Cooling

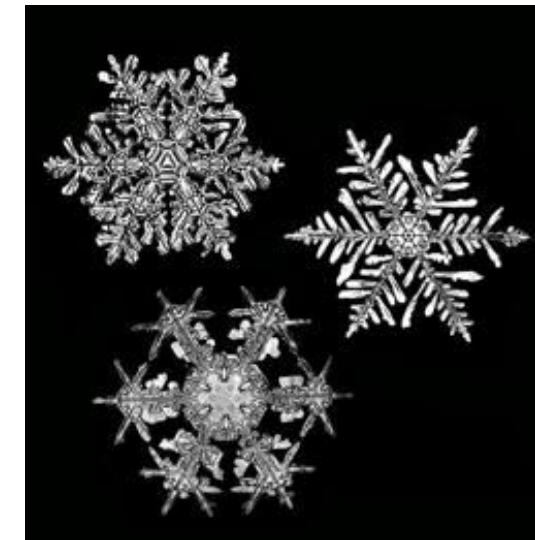
- Let's start by thinking about **cooling**:

- ✓ The universe began in a hot dense state (Big Bang) with (almost) no structure. Ever since then it has been **expanding and cooling**, causing various structures to “**condense out**”.
- ✓ E.g., at one time, all of space was filled basically with hot protons, neutrons, electrons, and photons (particles of light). As these gasses **cooled**, the electrons combined with the protons, resulting in **neutral hydrogen atoms condensing out**
- ✓ Because the electrons and protons were now together as hydrogen atoms (fewer possible arrangements), this condensation represented a **decrease in entropy/increase in order**. However, the *energy* released in this process, carried away and *spread out* as photons, represented **at least as great an increase in entropy/decrease in order**



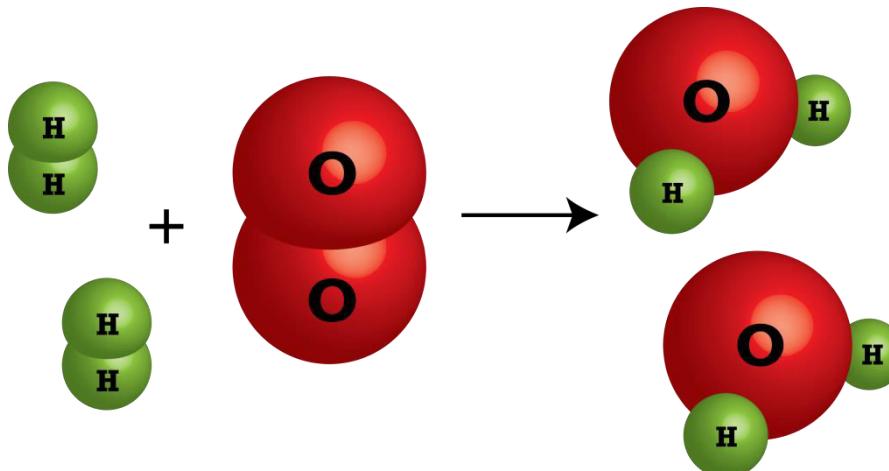
## Cooling

- The same thing happens when water molecules **condense** into snowflakes:
  - ✓ Ice is a **more ordered** structure than water vapor (less ways for the H<sub>2</sub>O molecules to be spread out, analogous to the [electron + proton → hydrogen] condensation), so the condensation of water molecules into snowflakes **reduces their entropy**.
  - ✓ But as discussed before, when water freezes, **energy is released** (analogous to the energy released as a photon when a hydrogen atom forms).
  - ✓ This energy warms the surrounding, cooler air molecules, which then take it away (like the dispersing photons). This **dispersal of thermal energy** represents a greater entropy increase than the water-to-ice entropy decrease → **net entropy increase**.
  - ✓ Aside: The 6- (or 3- or 12-) sided symmetry is a result of the underlying symmetry of the water molecule (quantum...)



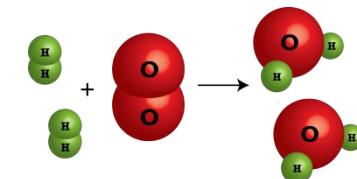
# Cooling

- Chemical reactions are the same: they are just a **type of cooling** (dispersal of energy).
- Example of **exothermic reaction**: the burning of hydrogen and oxygen gas:



## Cooling

- Chemical reactions are the same: they are just a **type of cooling** (dispersal of energy).
- Example of **exothermic reaction**: the burning of hydrogen and oxygen gas:
  - ✓  $2\text{H}_{2(g)} + \text{O}_{2(g)} \rightarrow 2\text{H}_2\text{O}_{(g)} + E$  (energy released)
  - ✓ Number of gas particles (per reaction) has **decreased** from 3 to 2. Fewer gas particles ⇒ fewer ways of arranging them ⇒ **decrease in entropy** (more order, like water-to-ice)
  - ✓ The electric field energy released (when the bonds change) goes into thermal energy (random KE) of the water molecules, then environment. This **increase in entropy**, by  $\Delta S = E/T$ , is **greater than the above decrease** (*many* ways of dispersing this energy)
  - ✓ This reaction is like water-to-ice cooling, except that the energy released is initially dispersed amongst the reaction products themselves (and then the environment)
  - ✓ Aside: Like many chemical reactions, an *activation energy* ("spark") is required...



# Cooling

- Key points:

- ✓ Chemical reactions happen **not** because the energy in the bonds decreases. (E.g., in **endothermic** reactions, energy must be *supplied*, and the energy in bonds **increases**.) Energy is always **conserved**, so reactions don't occur because of a “lowering of energy”.
- ✓ Chemical reactions are driven by the **dispersal of energy**, i.e., a reduction in the **quality** of the energy, **not the quantity**. More generally, the driving force of *any* natural process in the universe is the random, purposeless dispersal of energy—analogous to “cooling”.
- ✓ There are many chemical (and physical\*) reactions in which more structured (lower-entropy) products emerge **spontaneously** from less structured (higher-entropy) reactants, provided a compensating disorder is created in the surrounding environment.

\*E.g., Carnot cycle: reactant = hot source; product = ordered KE of piston; compensating disorder created in cold sink

# Cooling

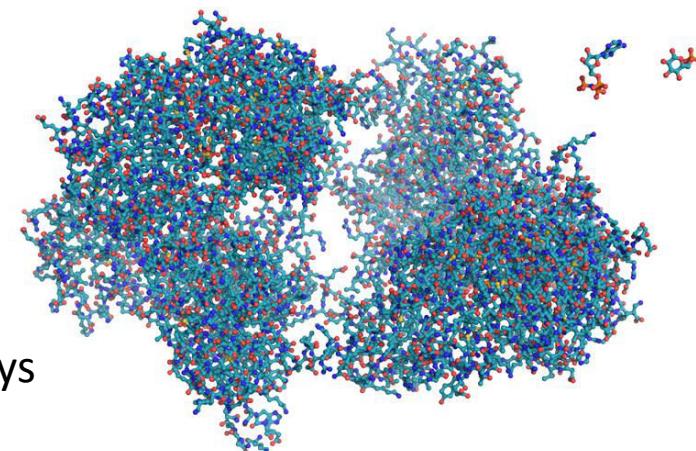
- So, assuming that life is just (complex) chemical reactions:

- ✓ Could nature ***spontaneously create***, as products of chemical “cooling”, the complex structures (machinery) of life, from less structured reactants?
- ✓ Would the very same “cooling” **animate** these machines?
- ✓ Is **human consciousness** just a (marvelous) form of “cooling” —just another way in which the universe cools as it expands?



# Proteins

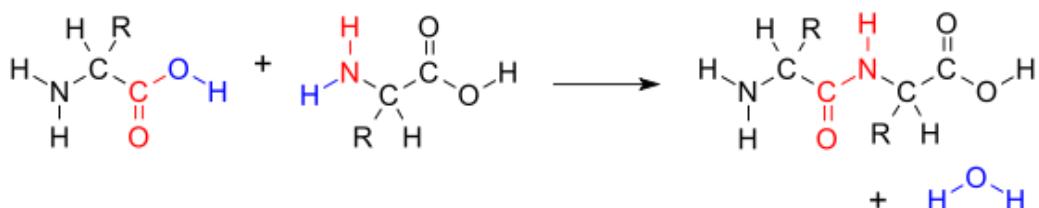
- Recall: **amino acids** are the building blocks of life. The human body uses 20 of them to construct **proteins**, the bulk of living stuff. The simplest amino acid is glycine.
- The **origin** of amino acids on the early Earth is not a big mystery. (Recall: Miller-Urey experiment, chemical reactions near deep-sea vents, material from space.)
- The bigger question is, how can amino acids **spontaneously** come together in the form of proteins? Two steps:
  - ✓ Amino acids link together in **long chains**
  - ✓ These chains **coil and fold/intertwine** in complex ways



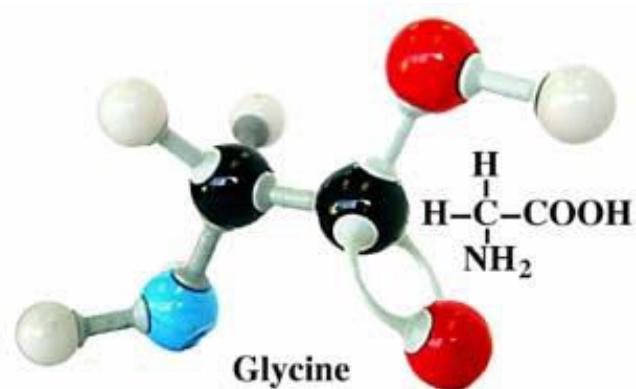
**typical protein**

# Formation of Amino Acid Chains

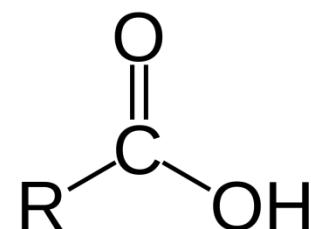
- Amino acids (e.g., glycine) have two key parts:
  - ✓ An  $\text{NH}_2$  *amine group*
  - ✓ A  $\text{COOH}$  *carboxylic acid group*
- Two amino acids join when the **amine group** in one approaches the **acid group** in the other, resulting in a **peptide bond** and the expulsion of a water molecule:



- This **consumes energy**, and is a big reason why we need to eat (more later...). But assuming we *have* a long chain of amino acids (a *peptide chain*), let's see how it **coils**.



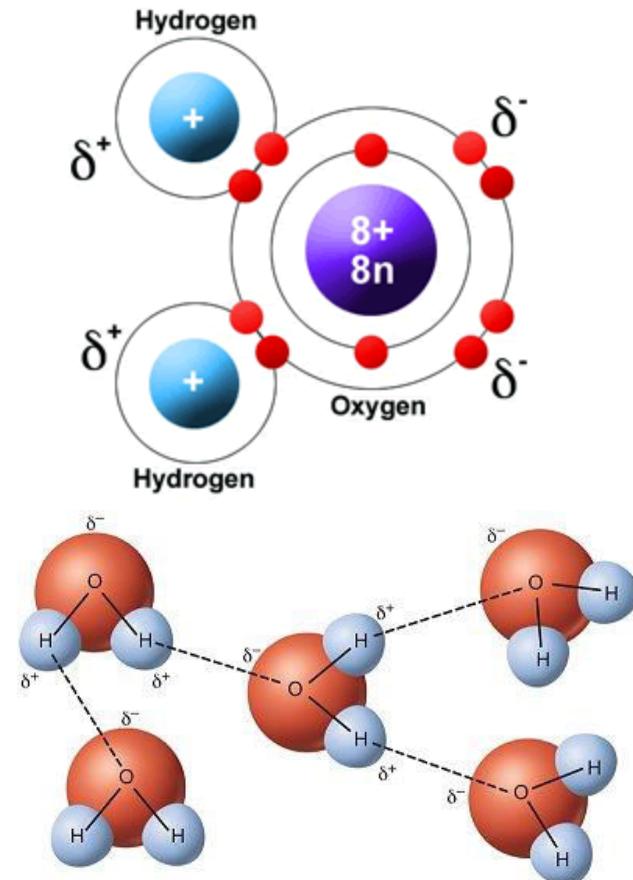
N=blue, C=black, O=red, H=white



carboxylic acid (note the OH)

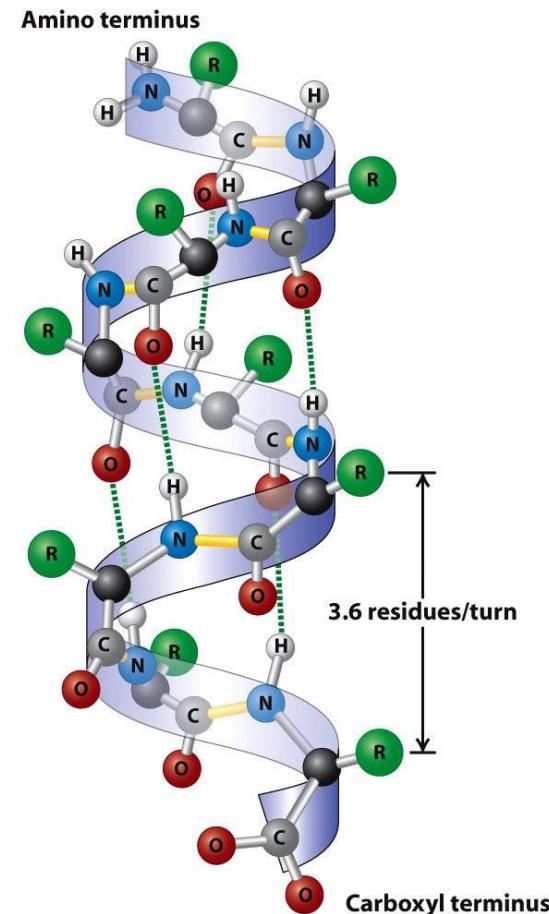
# Coiling of an Amino Acid Chain into a Helix

- The water molecule,  $\text{H}_2\text{O}$ , is a **polar molecule**: Each H shares its electron with the O, making the protruding Hs **positive**. Also, the O has four more unshared electrons, opposite the Hs, making the side of the O opposite the Hs **negative**.
- In **liquid water**, the positive Hs of one molecule attract the negative Os in neighboring molecules. This **hydrogen bond** is stronger than van der Waals interaction, and weaker than covalent or ionic bonds, and is responsible for various “magical” properties of water that make it integral to life.
- It’s also responsible for the **coiling** of amino acid chains into the very important **alpha helix**. The H attached to the N of one peptide bond **hydrogen-bonds** with the O attached to the C of a neighboring peptide bond. This bond is strong enough to hold the helical structure in place.



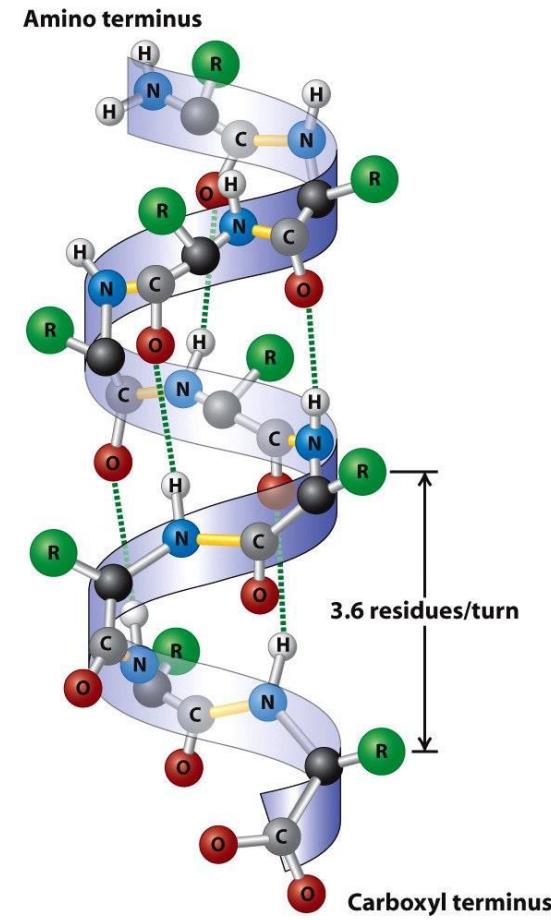
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# Coiling of an Amino Acid Chain into a Helix

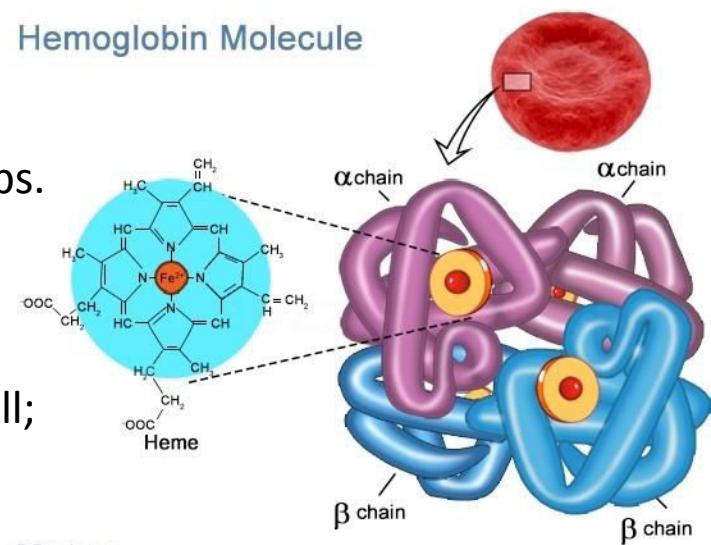
- The rigid alpha helix is a **more ordered** form of the amino acid chain, than just a random, floppy, linear chain. How can this order arise **spontaneously** (via the Second Law)?
- The O—H hydrogen bonds are sufficiently strong that, when they form, enough (electrostatic field) energy disperses into the environment (as thermal energy) that the resulting **increase in disorder** exceeds the increase in order of the alpha helix. The universe as a whole is **more disordered!**
- Moreover, the formation of the helix is **irreversible**: once the energy has dispersed, there's not enough concentrated energy around to break the bonds. (When you cook an egg, you're unzipping the helix.) This form of **local order** has "**condensed out**" of the universe's inexorable ratcheting towards **greater overall disorder!**  $\Delta S > 0$ .



# Folding and Intertwining of Helices

- **Hemoglobin molecules** (making up 96% of the non-water in red blood cells) carry **oxygen** to all the cells in your body.
- Each molecule is made of two alpha and two beta helices, bent and twisted in such a way as to hold four **heme** groups. Each heme group has one **iron atom** that oxygen binds to. (Blood is red because iron oxide is rust. So eat your iron!)
- The bending and twisting of the helices is not random at all; it is very precise. Each red blood cell contains zillions of **identical** hemoglobin molecules. Hemoglobin is a **highly ordered** structure. Can such order emerge **spontaneously**?
- **Yes**, in part for the same reason oil and water don't mix...

Hemoglobin Molecule



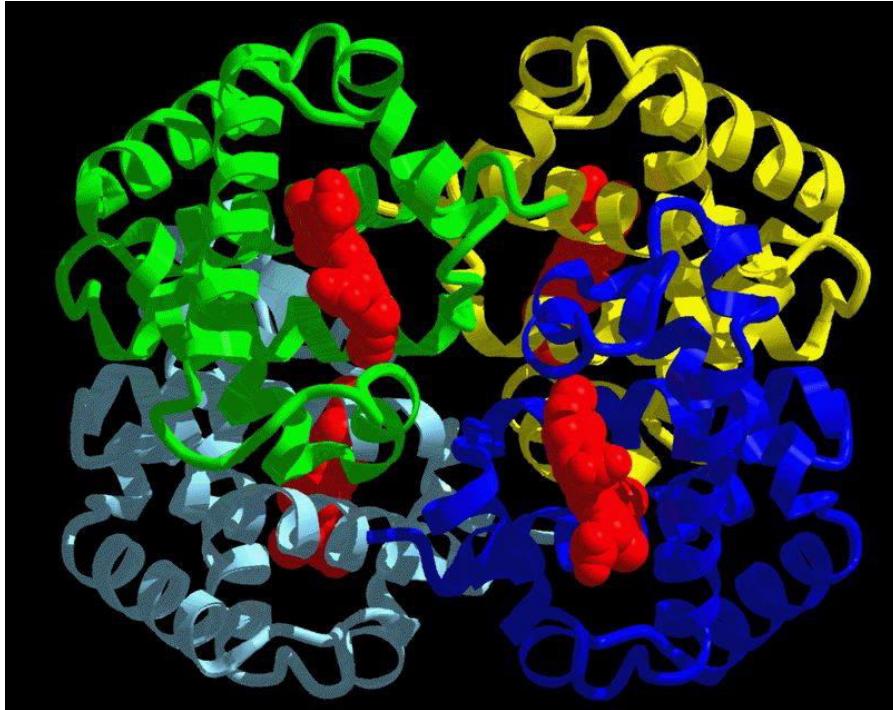
# Folding and Intertwining of Helices

- Why doesn't oil **disperse** in water, like a drop of ink? Surely this would **increase the entropy** of the universe, and so be spontaneous? Why does it do the **opposite**: clump together after we try to mix it?
- Hydrocarbons (like oil) are made of only C & H atoms, and are **hydrophobic**: when a hydrocarbon molecule is put in water, the surrounding (polar) water molecules interact with its H atoms and form a **highly structured** cage around it. (E.g., methane =  $\text{CH}_4$ .)
- The resulting **increase in order** would outweigh the **decrease in order** caused by the spreading out of the oil molecules (and their energy). Oil molecules clump together to show as few of the themselves to the water as possible: hydrophobic = water-hating.
- What does this have to do with folding & intertwining of helices?



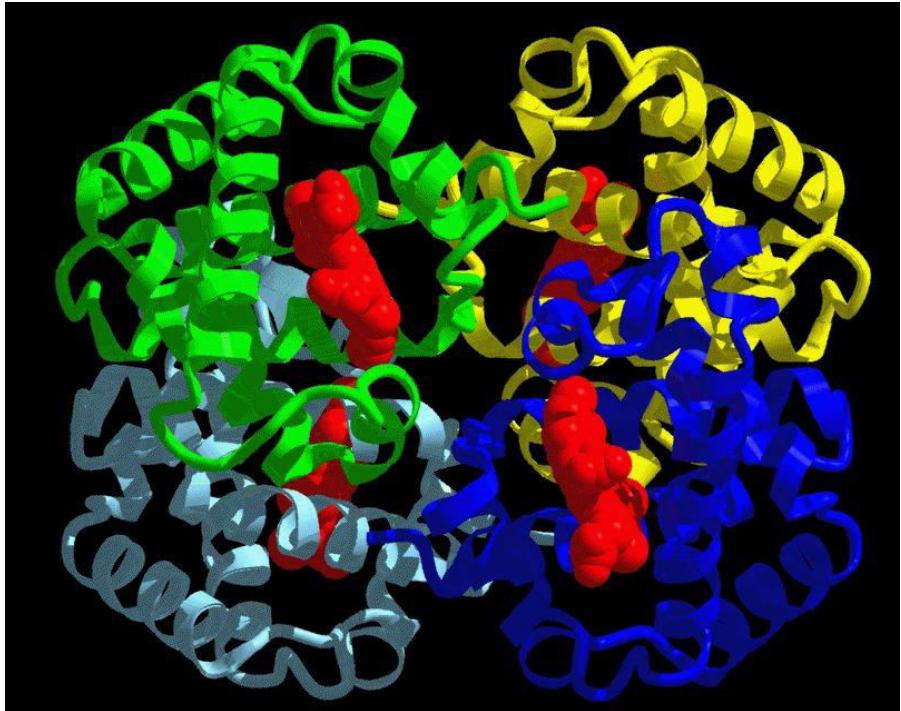
# Folding and Intertwining of Helices

- Many of the amino acids in the helices have **hydrocarbon parts**, and so **behave like oil** (hydrophobic).
- Water molecules would form **intricate cages** around any hydrocarbon parts sticking out into the surrounding water, **increasing the order** in the universe.
- The helices fold in ways that tend to **minimize** exposure of hydrocarbon parts to the water, and thus **minimize order (maximize disorder)**.
- The same effect probably plays a role also in the four helices **intertwining** in hemoglobin.



The formation of this complex structure increases the disorder of the universe

# Folding and Intertwining of Helices

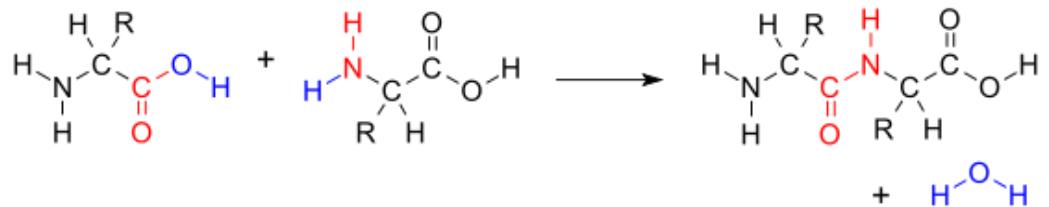


=



# Formation of Amino Acid Chains

- But how are amino acid chains formed **in the first place?**
- Recall that forming the peptide bonds between the amino acids in a chain **consumes energy**.



- So the short answer is obvious:  
**We eat food that provides this energy.**
- But the long answer is more interesting...



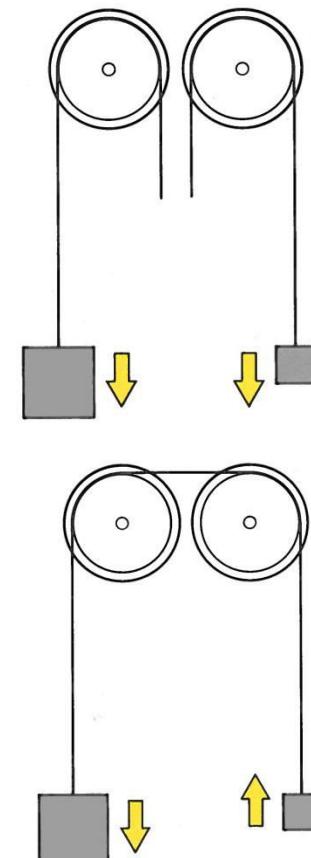
# Formation of Amino Acid Chains

- The ordered chain has more structure (**lower entropy**) than the scattered amino acids it was made from. Thus, there must be a **compensating disorder** created elsewhere. **How?**
- We eat, in part for the energy, but more importantly: we take in **high quality** (low entropy) energy, and allow it to **decay to low quality** (high entropy) energy, which we expel as body heat and excrement. This **spontaneous order-to-disorder** process *drives non-spontaneous disorder-to-order* processes in our bodies, sustaining our relatively low entropy bodies against decay, and thus staving off death.
- This **low entropy energy** ultimately comes from the **Sun**, or more ultimately, from the **Big Bang** itself. Life is **intimately connected** with the very *dynamics of the universe itself*. Life is **not** an *isolated* phenomenon. “**Biosphere**= Universe!”



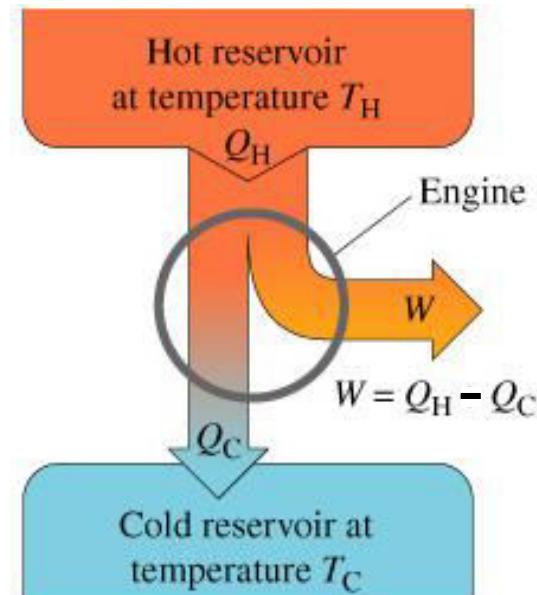
# Coupling Spontaneous to Non-Spontaneous Processes

- “This spontaneous order-to-disorder process *drives non-spontaneous disorder-to-order* processes in our bodies.”  
**HOW??**
- Analogy:
  - ✓ **Top Picture:** Both masses will **spontaneously** fall.
  - ✓ **Bottom Picture:** When **coupled together**, the heavier mass will raise the lighter. A **stronger** spontaneous reaction can ***drive*** a weaker spontaneous reaction in the **reverse (non-spontaneous or unnatural) direction**.
- Questions:
  - ✓ How do we assess the “**driving power**” of a reaction?
  - ✓ What are the “gears and wheels” that **couple** life’s chemical reactions?



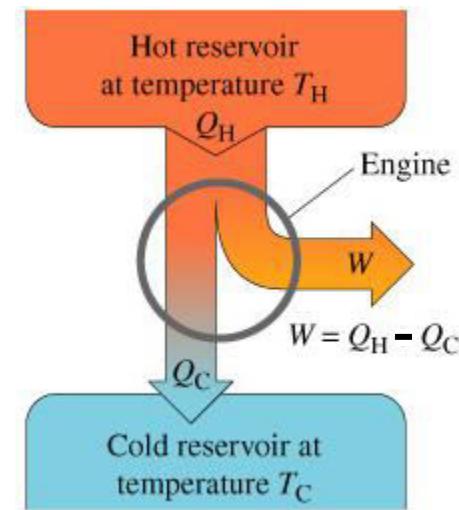
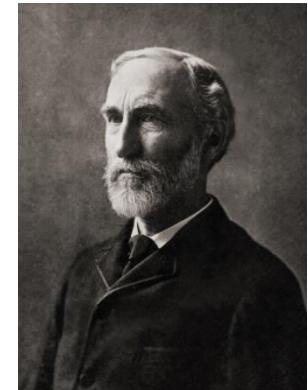
# Driving Power of a Reaction

- Recall:
  - ✓ In a heat engine, the **spontaneous** flow of thermal energy from hot to cold is **harnessed** to do useful work,  $W$ , which can be used to **create structure and order**. “Order from disorder”.
  - ✓ But not all of  $Q_H$  is converted into useful work,  $W$ . A minimum of “waste heat”  $Q_C$  (unusable energy) must be dumped into the environment (increasing its entropy) to ensure **net entropy increase** for the universe.
  - ✓ The amount of energy that is **free to do work** (create structure and order) is called the **free energy**. For a heat engine, the free energy available goes **down** as it does work:  $\Delta F = -W$ . What about in the case of chemistry?



# Driving Power of a Reaction

- Josiah Gibbs (1839–1903), in Boltzmann's generation, was the first person to **apply thermodynamics to chemistry**, and hence make thermodynamics more readily applicable to life.
- E.g., we can think of an **exothermic** chemical reaction as a heat source with total energy  $U$  at temperature  $T_H$ . When the system liberates energy  $Q_H$ , its energy goes **down**:  $\Delta U = -Q_H$ , and its entropy is **reduced**:  $\Delta S = -Q_H/T_H$ .
- In order for this to happen **spontaneously**, a minimum of “waste heat”  $Q_C$  (unusable energy) must be dumped into the environment (at temp  $T = T_C$ ), **increasing** its entropy by (at least) the same amount:  $\Delta S_{\text{env}} = -\Delta S = Q_H/T_H = Q_C/T$ . Like the heat engine, the free energy of the system goes **down** as it does work:  $\Delta F = -W = -Q_H + Q_C = \Delta U - T\Delta S$ .



# Driving Power of a Reaction

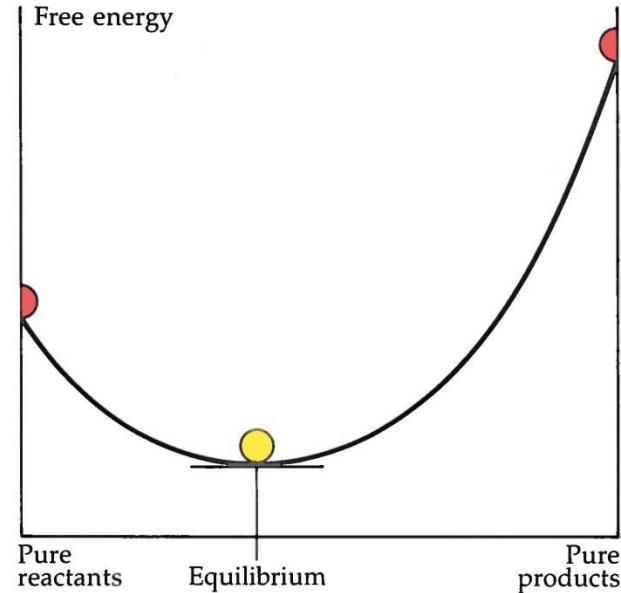
- All chemical reactions **spontaneously** move towards **lower free energy**:

$$\Delta F = \Delta U - T\Delta S < 0$$

- This is the “**driving power**” of the reaction: the greater the “fall” in free energy, the more **useable energy** (“work”) is liberated to **create structure and order** elsewhere.

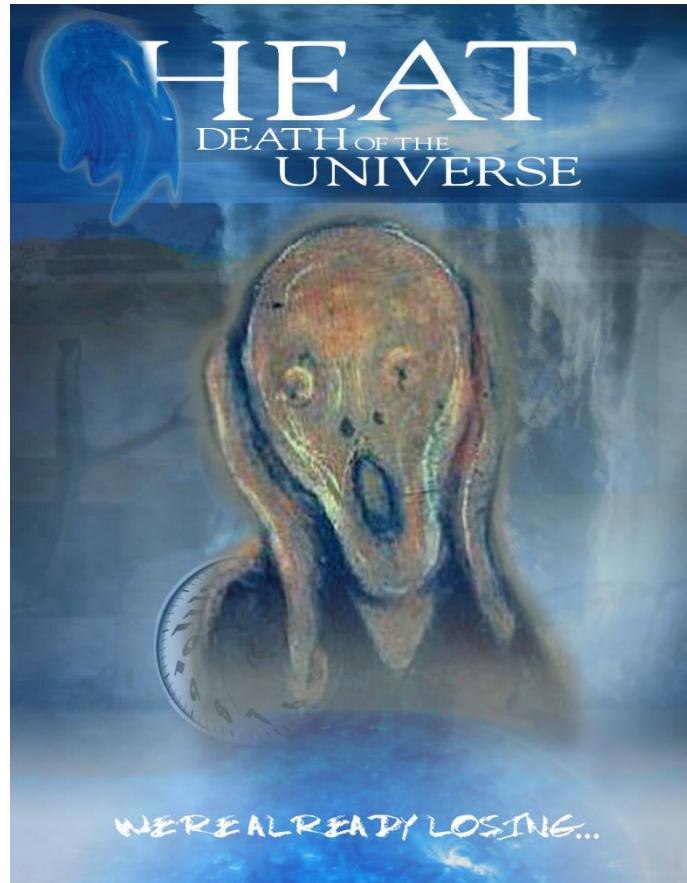
- This applies to **all natural processes** in the universe:

- ✓ Systems do **not** spontaneously move to **lower energy** (e.g.,  $\Delta U > 0$  when you heat a gas).
- ✓ Systems spontaneously move to **lower free energy**. This drives **all** process, including **animating life**.
- ✓ Systems fall **down** in free energy, as the universe falls **up** in total entropy.



# The End of Free Energy

As the total entropy of the universe steadily ratchets up, we are not running out of energy (energy is **conserved—eternal**). We are running out of **free** energy. **Useful** energy. Energy that can be used to **create structure and order, and animate life.**

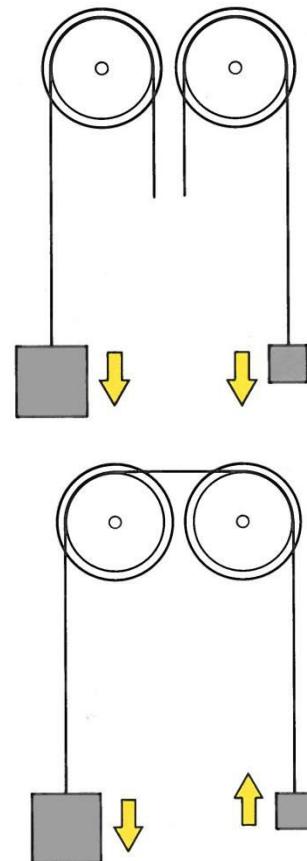
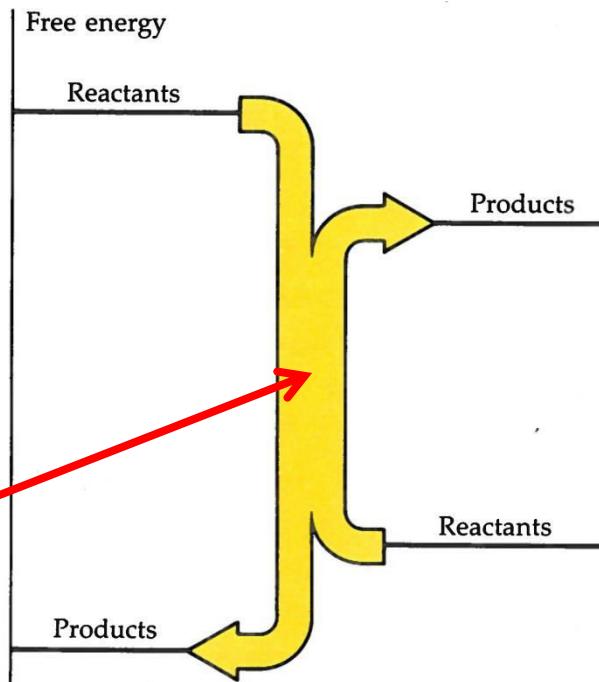


# Coupling Reactions

- How does this inexorable slide into disorder animate life?

When **coupled** together, a reaction that **falls further** in free energy (a more vigorous slide into disorder) can **drive** one that **falls less** in free energy (less vigorous slide into disorder) in the **reverse direction**.

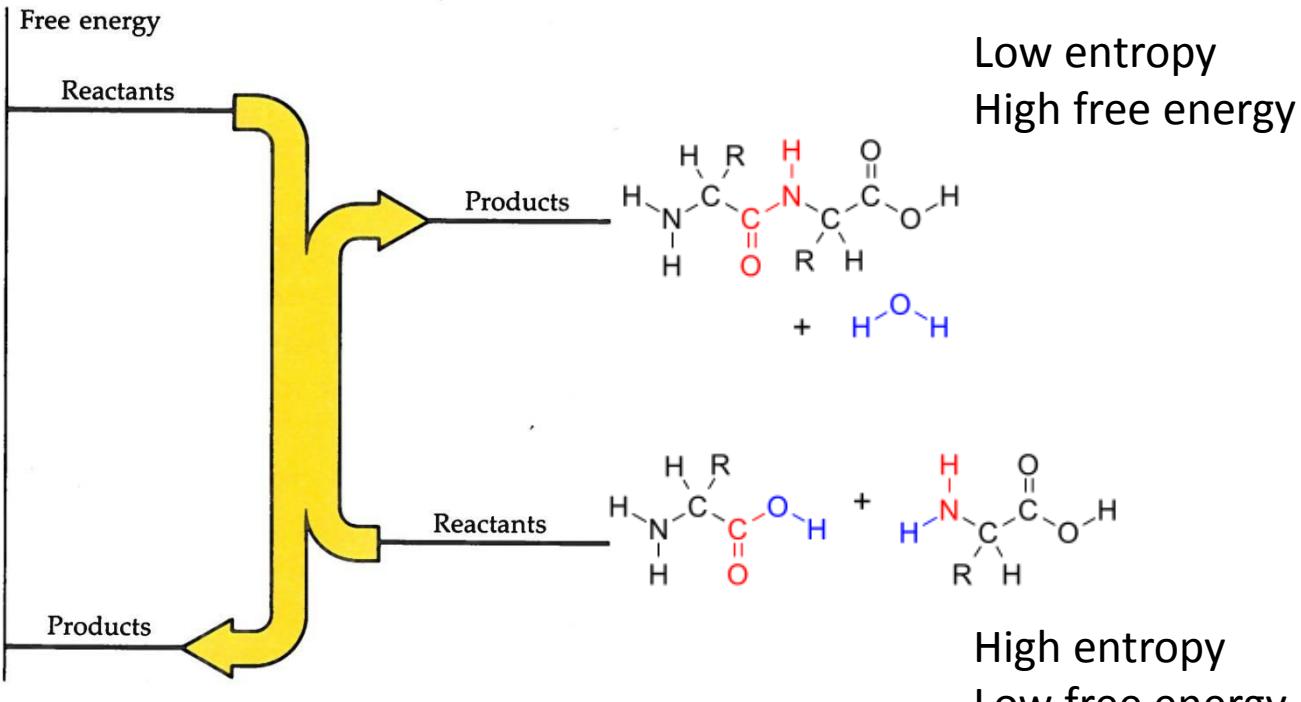
Life's “gears and wheels”



# Example: Bioenergetics Coupled to Biosynthesis

Bioenergetics (LEFT: degradation of food) **coupled** to Biosynthesis (RIGHT: linking amino acids)

Low entropy  
High free energy



High entropy  
Low free energy



# The Gears of Biosynthesis

Let's first look at some of the “gears” of Biosynthesis (RIGHT)



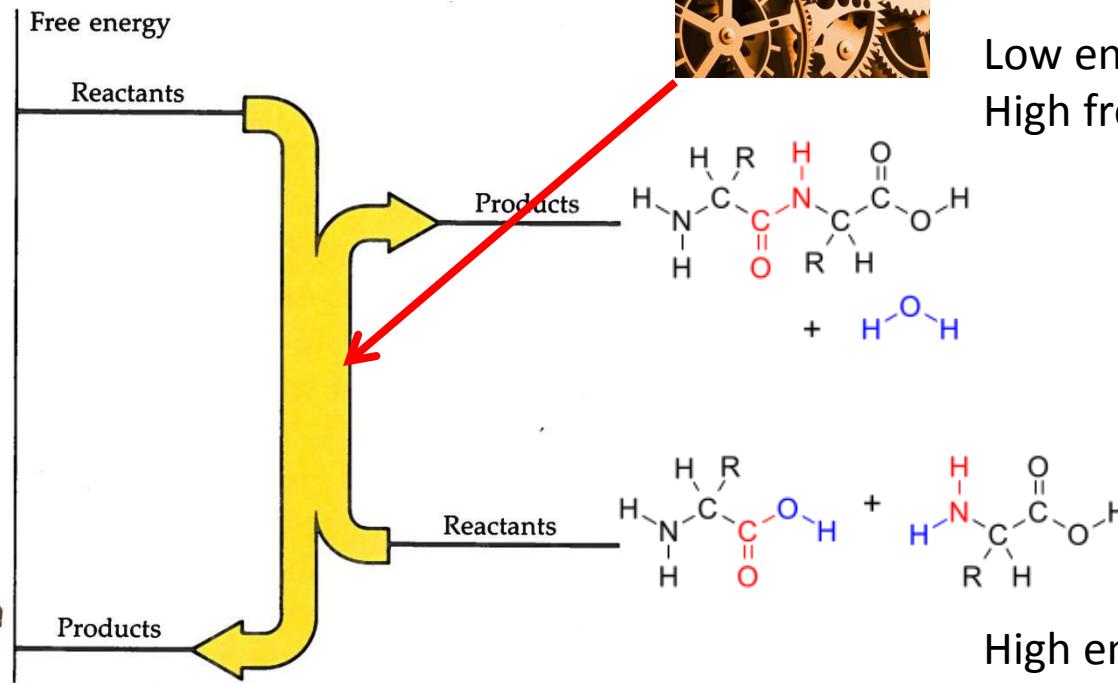
Low entropy  
High free energy



Low entropy  
High free energy



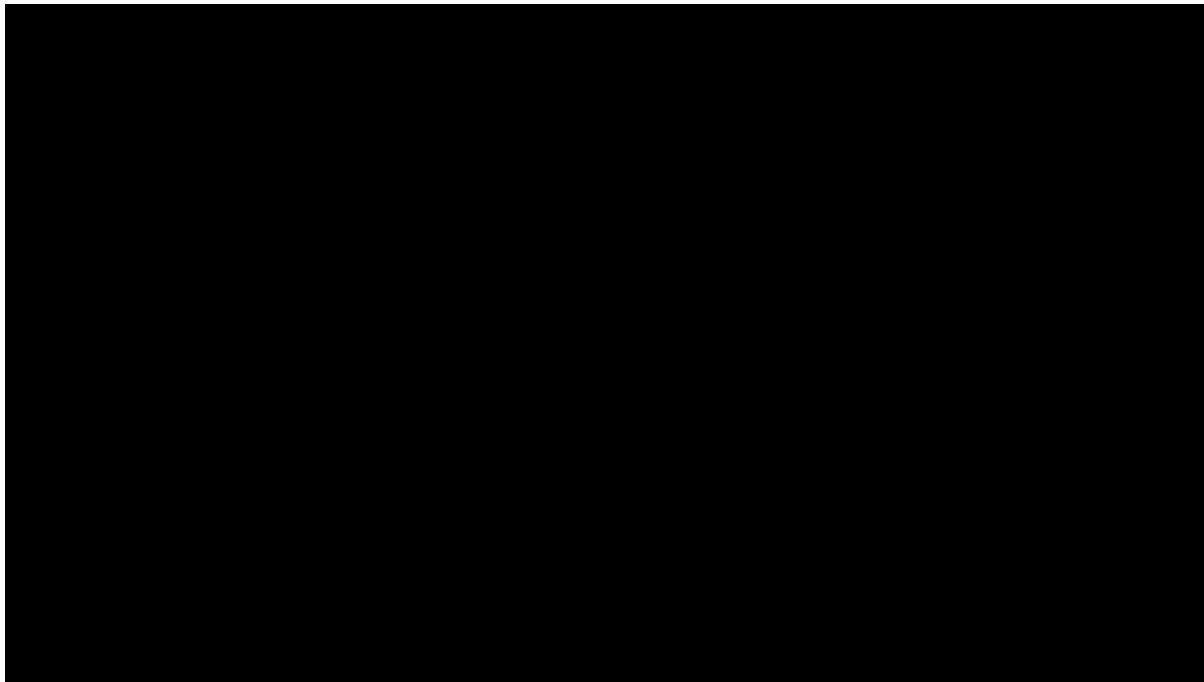
High entropy  
Low free energy



High entropy  
Low free energy

# The Gears of Biosynthesis

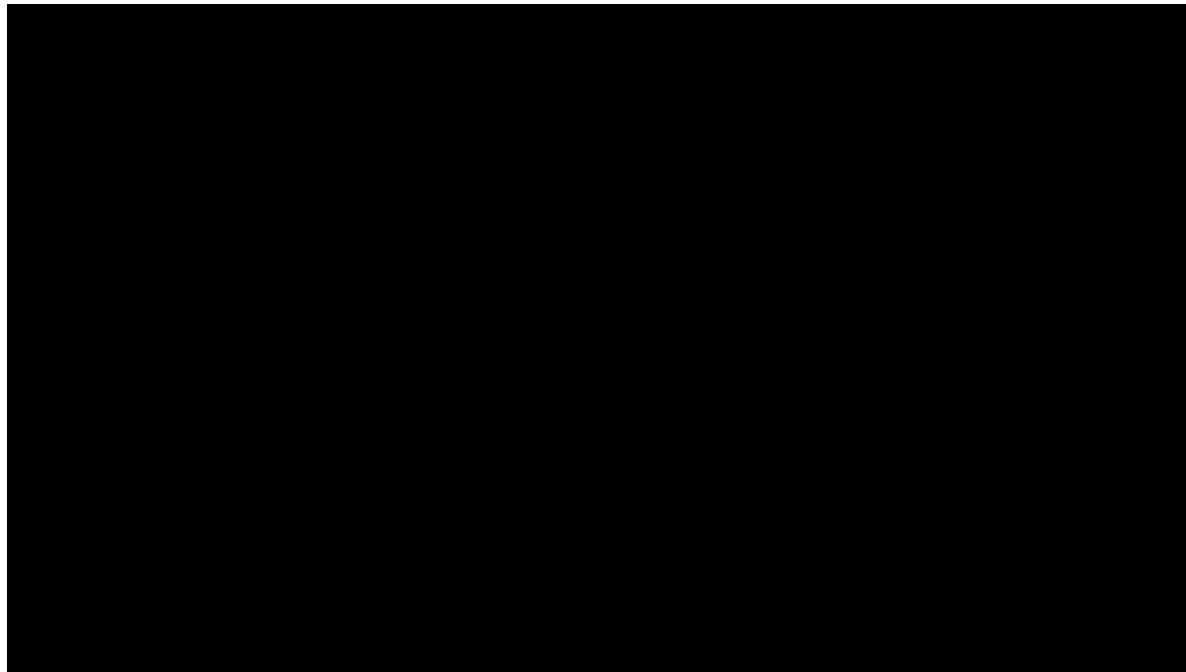
**It's complicated...**



<https://www.youtube.com/watch?v=gG7uCskUOrA>

# The Gears of Biosynthesis

**It's complicated...**



<https://www.youtube.com/watch?v=WFCvkkDSfIU>

# The Gears of Biosynthesis

**It's complicated...**

**Other similar animations, emphasizing different aspects:**

<https://www.youtube.com/watch?v=D3fOXt4MrOM>

<https://www.youtube.com/watch?v=lpb5s2F1pyM>

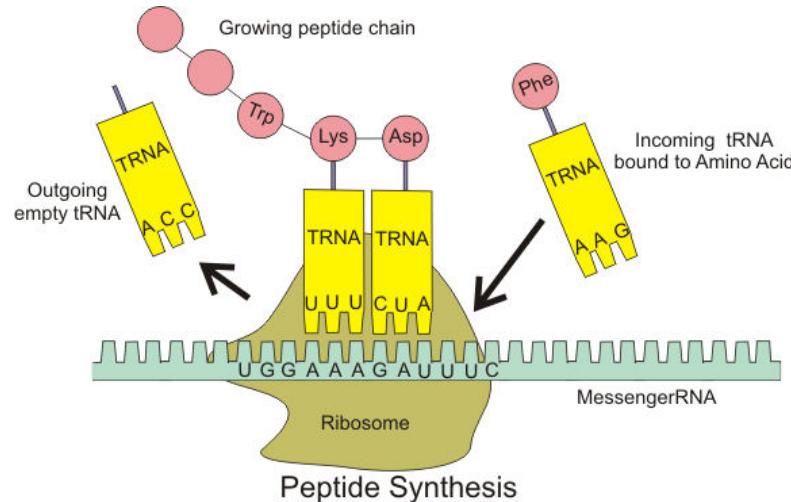
<https://www.youtube.com/watch?v=28mgfg8nRT4>

<https://www.youtube.com/watch?v=JX2MdZX6Bys>

[https://www.youtube.com/watch?v=B\\_zD3NxSsD8](https://www.youtube.com/watch?v=B_zD3NxSsD8)

# The Gears of Biosynthesis

The “gears” of biosynthesis are **highly complex, microscopic machines!**



How could they *possibly* arise spontaneously?

We'll return to this question later...

First we'll look at some “gears” (microscopic machines) of bioenergetics

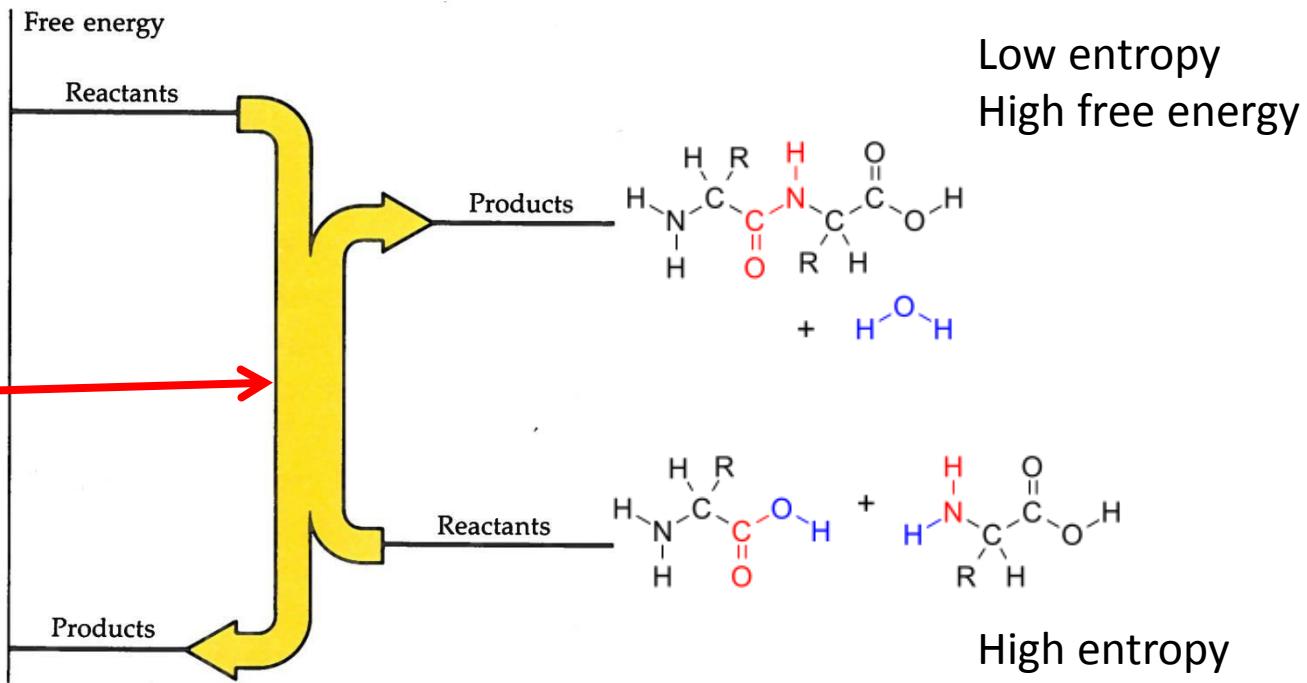
# The Gears of Bioenergetics

Let's now look at some of the “gears” of Bioenergetics (LEFT)

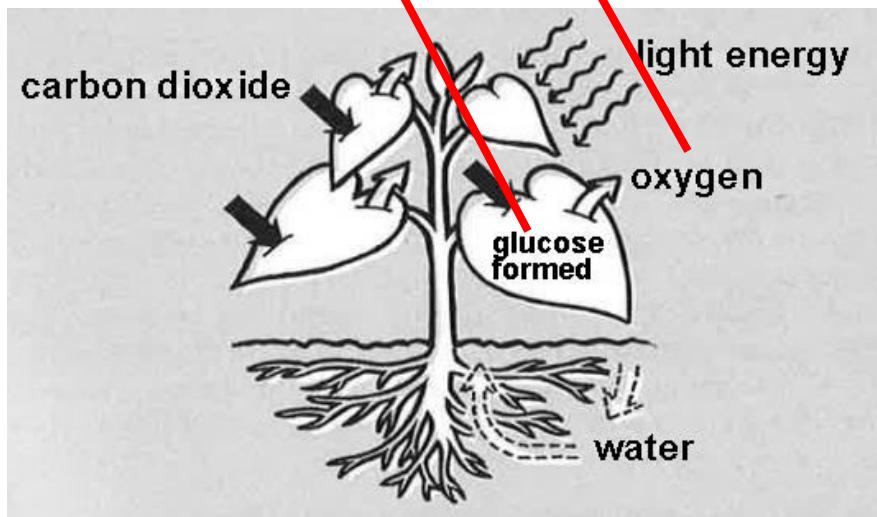
Low entropy  
High free energy



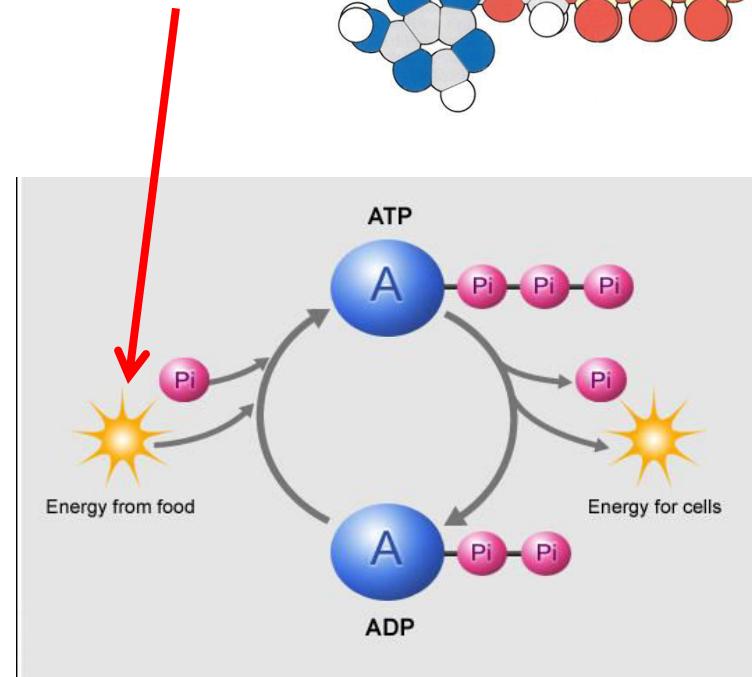
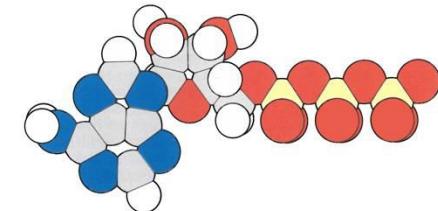
High entropy  
Low free energy



# The Gears of Bioenergetics

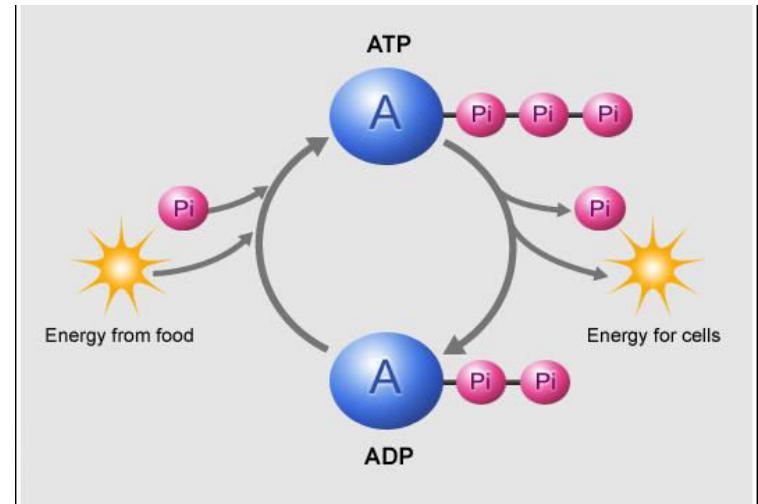
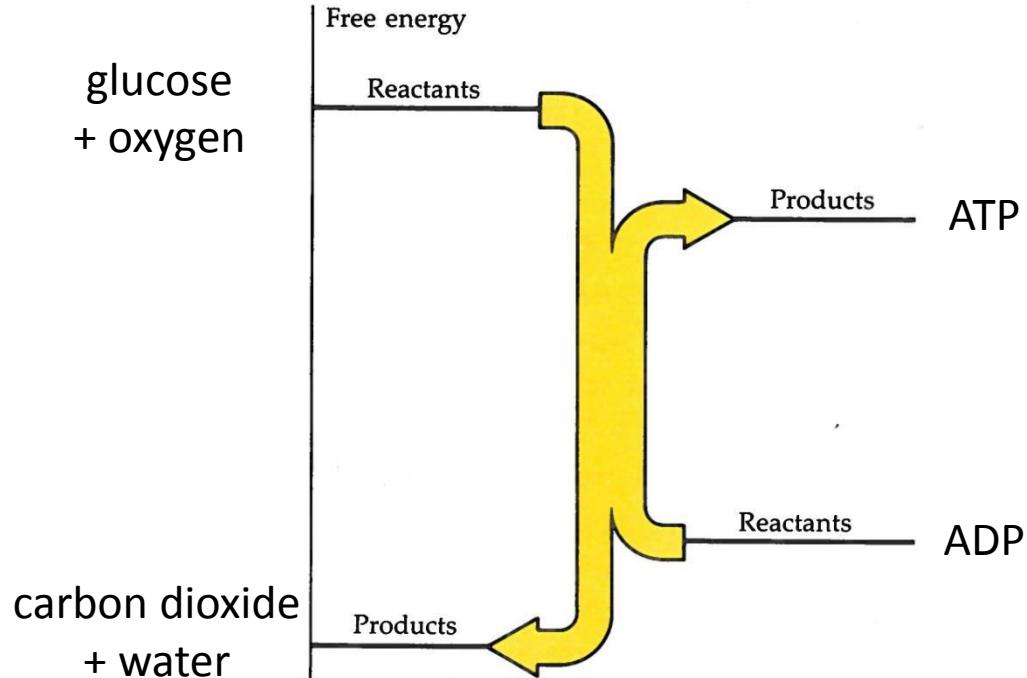


photosynthesis (more later...)



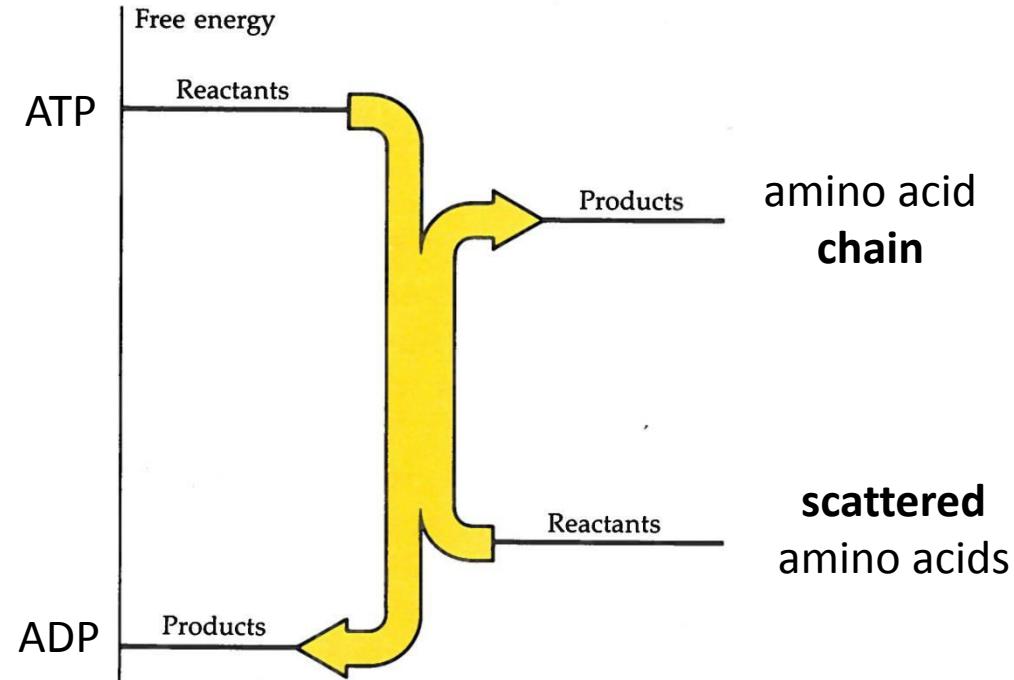
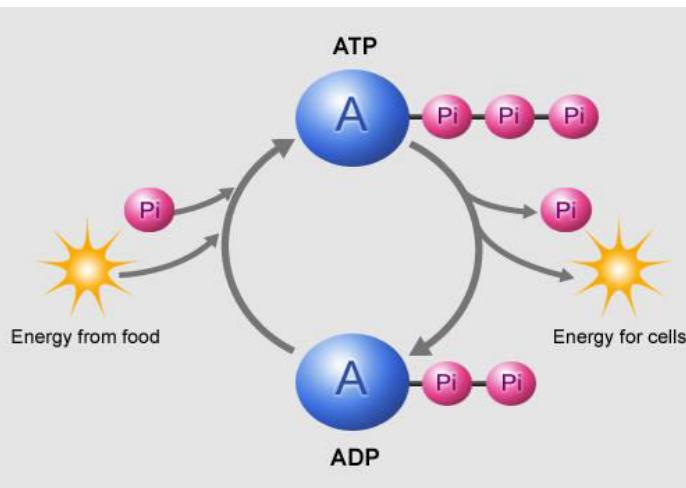
adenosine diphosphate  $\rightarrow$  triphosphate ( $\text{PO}_4$ )

# The Gears of Bioenergetics



This is a **spontaneous** process that increases the entropy of the universe

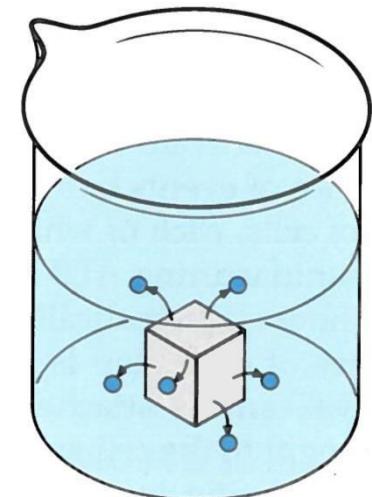
# The Gears of Bioenergetics



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# The Gears of Bioenergetics

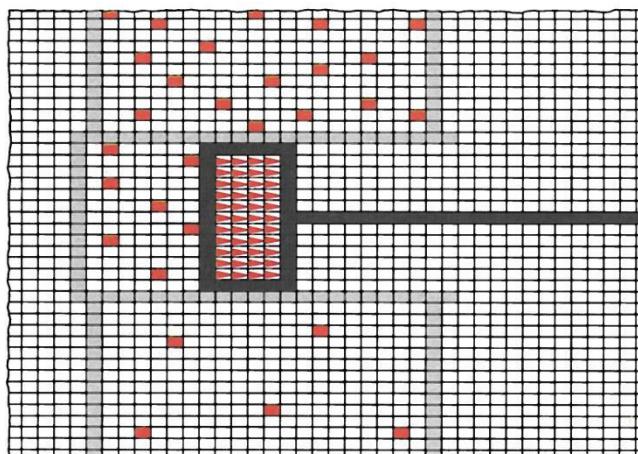
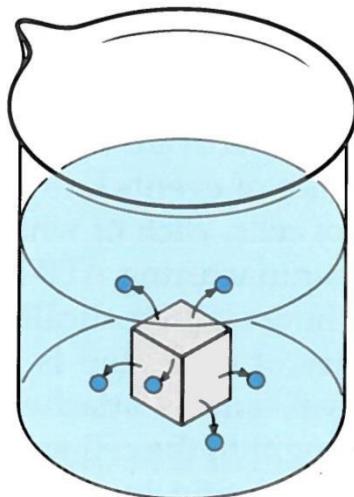
- ADP & ATP are the **life blood** of bioenergetics
- The energetic “charging” of ADP to ATP is done by an **electrochemical battery**
- **Example** of electrochemical battery:
  - ✓ Drop a cube of **iron** (Fe) into a **copper** (Cu) sulfate solution
  - ✓ The **Cu<sup>2+</sup> ions** in the water have a **strong affinity** for electrons
  - ✓ When they touch the cube, the **Fe atoms** give up 2 electrons to the **Cu<sup>2+</sup> ions**. The Fe atoms become **Fe<sup>2+</sup> ions** in solution, & the Cu<sup>2+</sup> ions become neutral **Cu atoms** that deposit on the cube
  - ✓ **Net result:** the **copper precipitates** and the **iron dissolves**



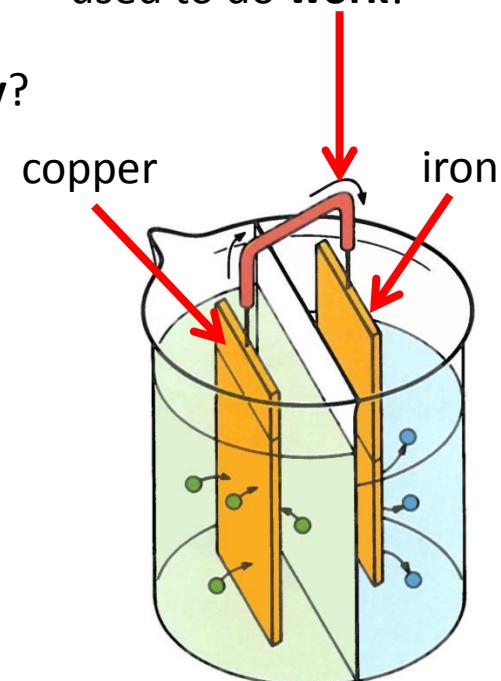
# The Gears of Bioenergetics

- Key Idea:

- ✓ As it stands, the ***spontaneous flow*** of electrons from the **Fe atoms** to the **Cu<sup>2+</sup> ions** is in **random directions**.
- ✓ What if we force the electrons to flow in **one direction only**?  
(Exactly like we extracted **ordered KE** in the heat engine!)



Electric current (opposite electron flow) can be used to do **work!**



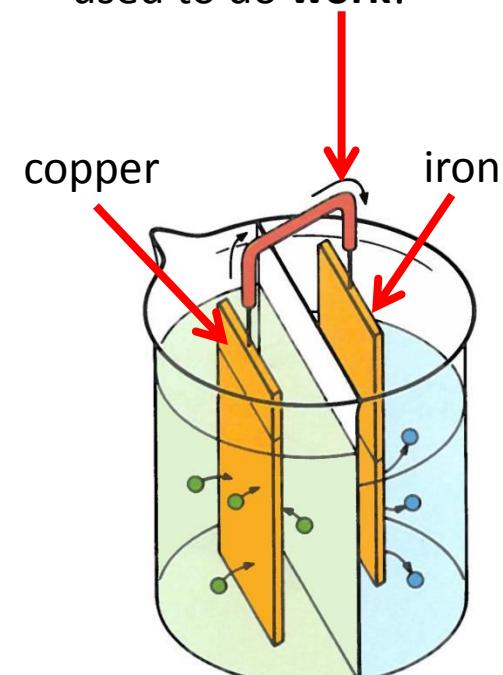
ignoring “salt bridge”...

# The Gears of Bioenergetics

- **Aside:**

- ✓ Where does the energy released by such a copper-iron battery actually come from?
- ✓ The nuclear furnaces in long-dead stars, which created the elements heavier than hydrogen, up to iron.
- ✓ Fission reactors today use uranium, which is created when stars explode as supernovae.
- ✓ Fusion reactors being developed today will use hydrogen, which was created by the Big Bang itself. **It is the most ancient (and abundant) of all fossil fuels.**

Electric current (opposite electron flow) can be used to do **work!**



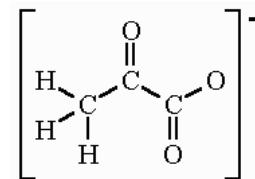
ignoring “salt bridge”...

# The Gears of Bioenergetics

- Nature has evolved a similar battery, in which glucose & oxygen are “burned” to charge ADP to ATP:

✓ Like Cu<sup>2+</sup> ions, **oxygen** has a **strong affinity** for electrons; it likes to become O<sup>2-</sup>

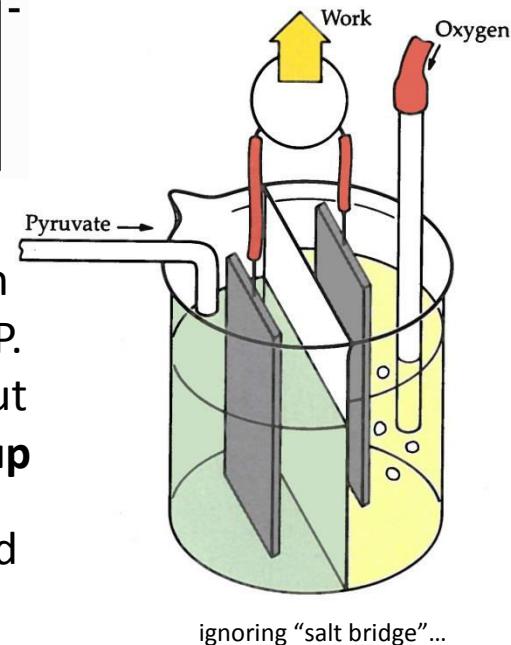
✓ Glucose gets “snipped” into two **pyruvate** ions:  
(which can easily give up their extra electron)  
...and two **protons** (H<sup>+</sup> ions) are produced



✓ The **spontaneous flow** of electrons from pyruvate to oxygen (the “burning of sugar”) does the work to charge ADP to ATP. The ATP have higher order (**lower entropy**) than the ADP, but with everything else, the **net** entropy of the universe **goes up**

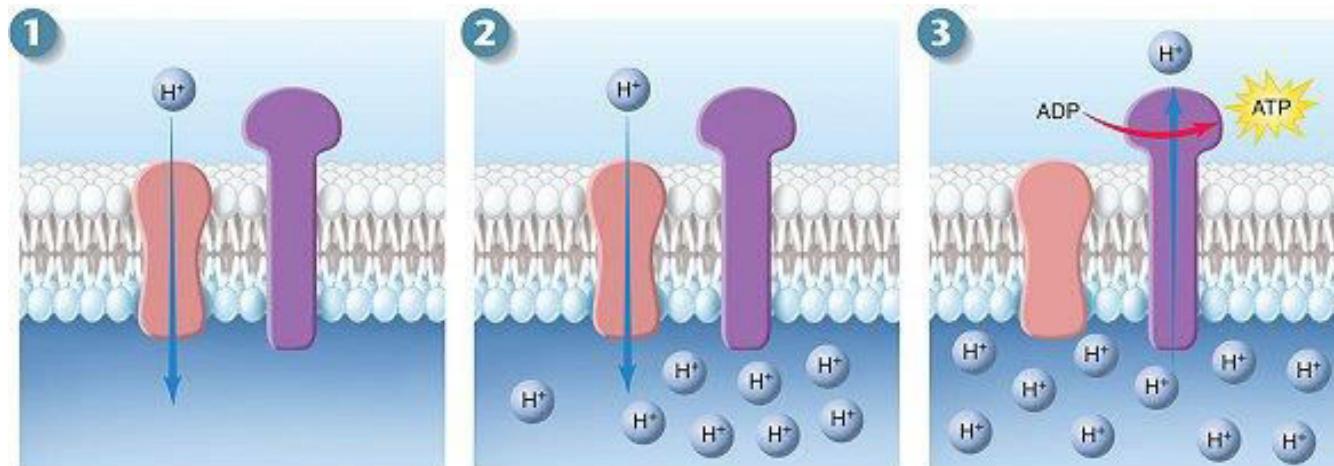
✓ The pyruvate falls apart into carbon dioxide (we exhale), and each O<sup>2-</sup> picks up two **protons** to become water...

13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
B Boron 12.811	C Carbon 12.011	N Nitrogen 14.067	O Oxygen 15.999	F Fluorine 18.998	He Helium 4.003



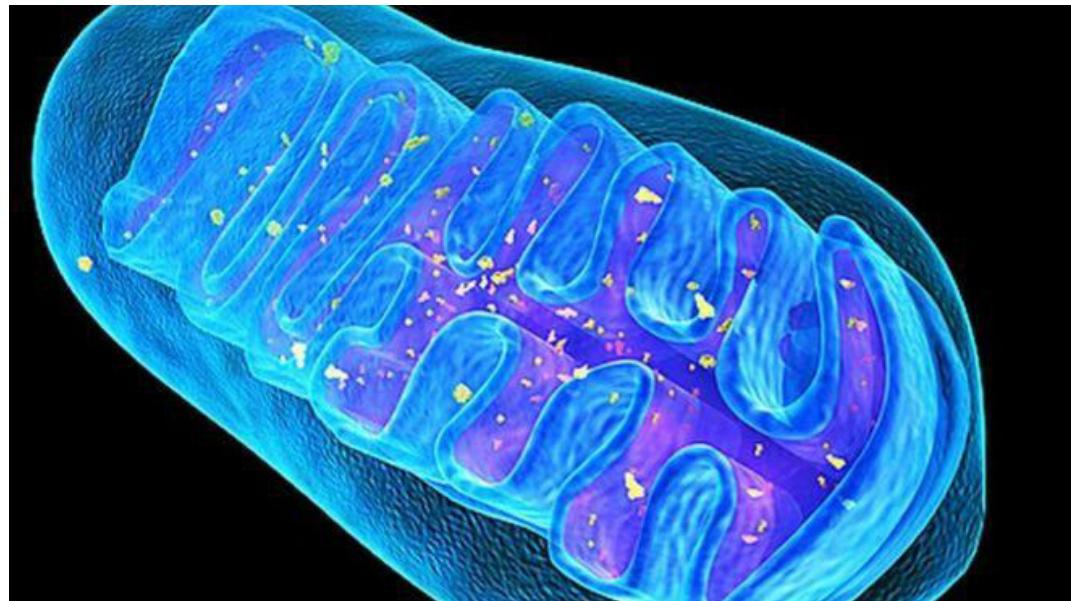
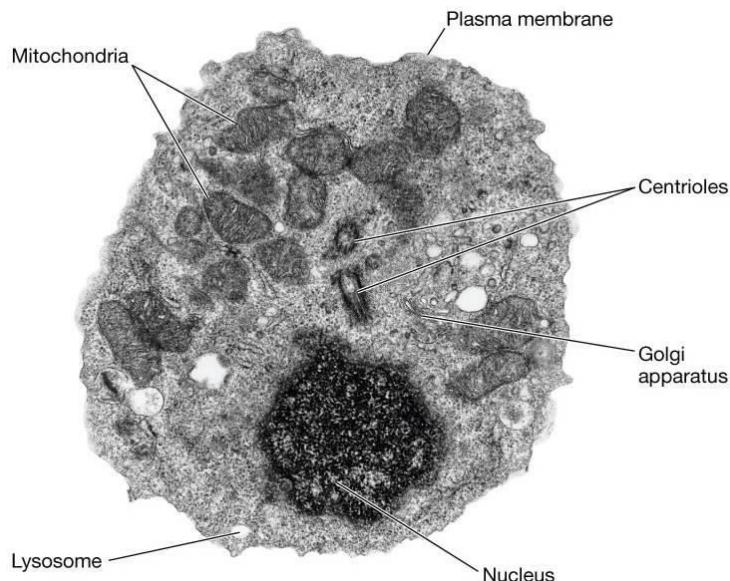
# The Proton Gradient

- The spontaneous flow of electrons **does not directly** charge the ADP to ATP. Instead:
  1. It drives a **proton pump** that forces protons across a membrane
  2. This creates a **proton gradient** that stores potential energy across the membrane (in an **electric field**).
  3. This **store of energy** can be tapped by allowing protons to flow back across the membrane through an protein called **ATP synthase**. The **electric field accelerates the protons**, and this extra **kinetic energy** is used to charge ADP to ATP.



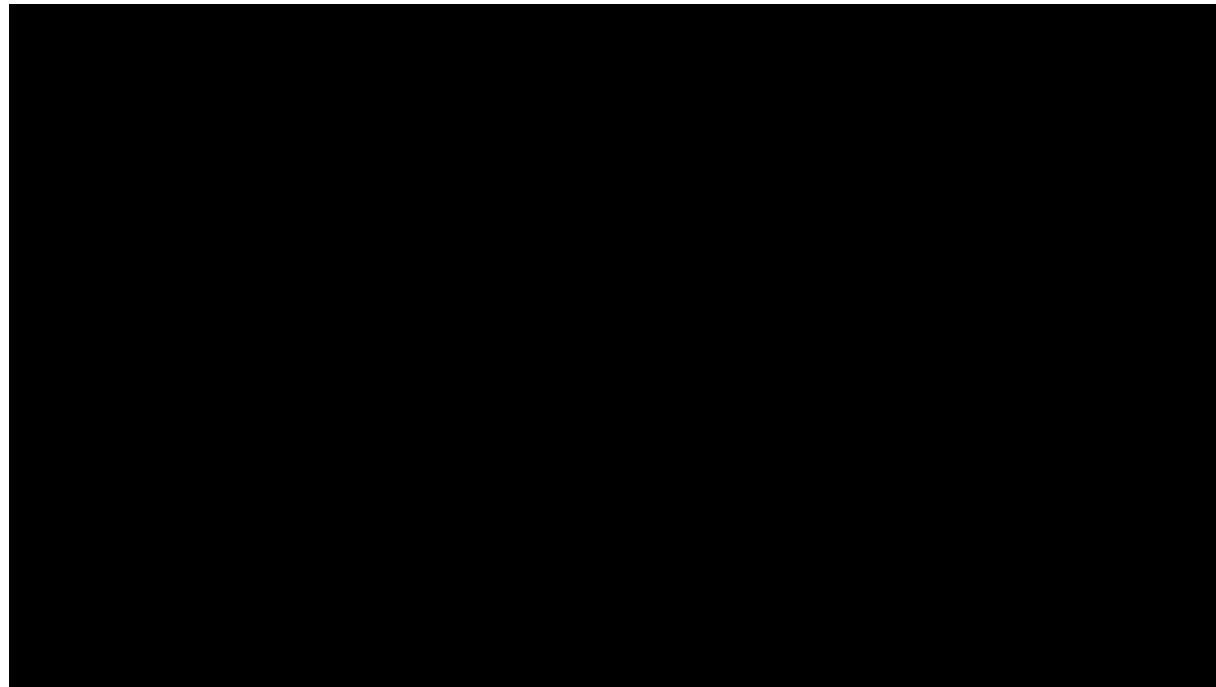
# The Proton Gradient

- All of this takes place in **mitochondria** inside cells:



# The Proton Gradient

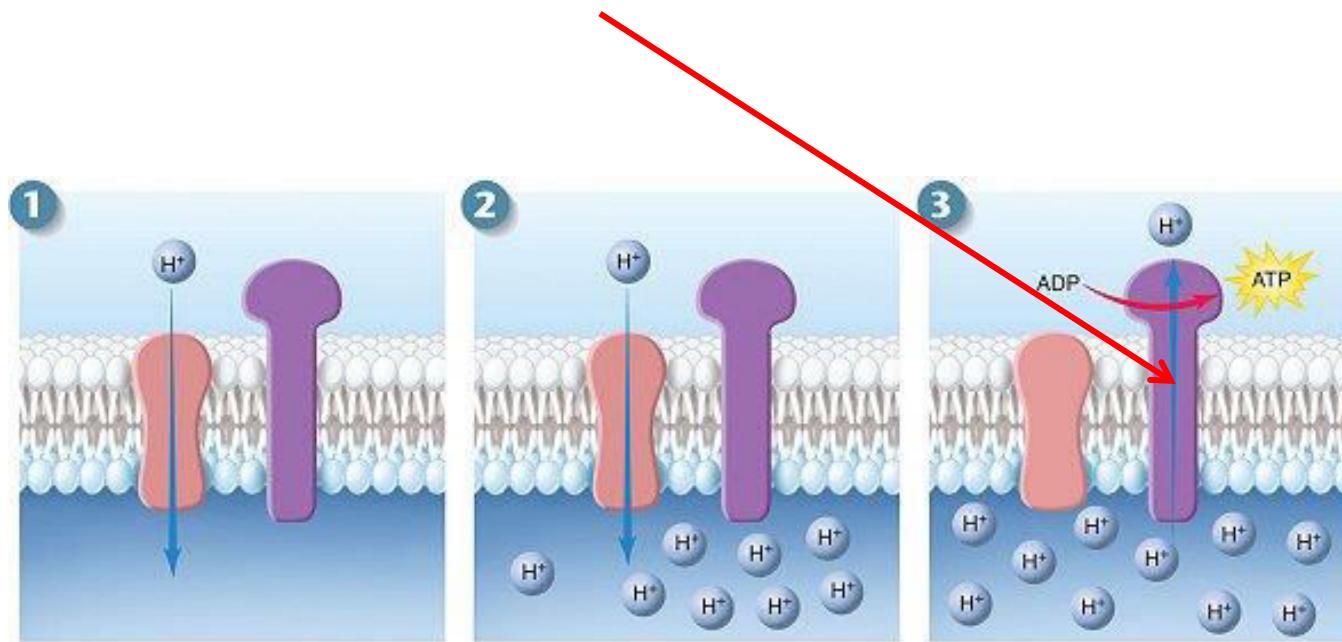
- All of this takes place in **mitochondria** inside cells:



<https://www.youtube.com/watch?v=nD9fyuisMkg>

# The Proton Gradient

- Let's look at how **ATP synthase** actually **works...**

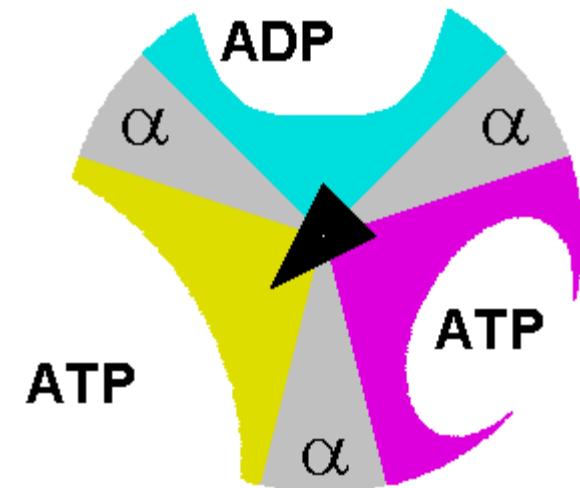
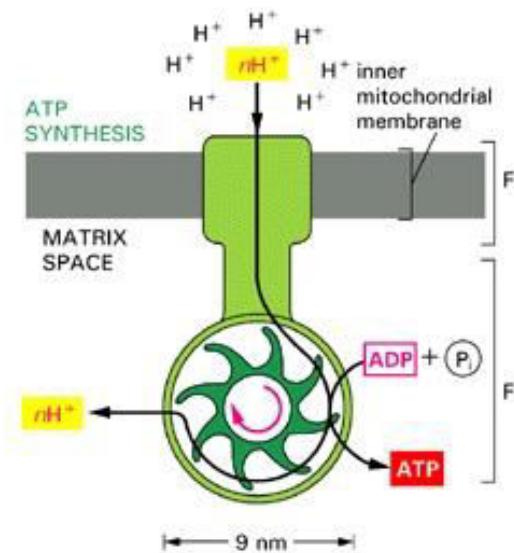


# The Proton Gradient

The **proton gradient** creates an **electric field** that **accelerates** the protons let back across the membrane.

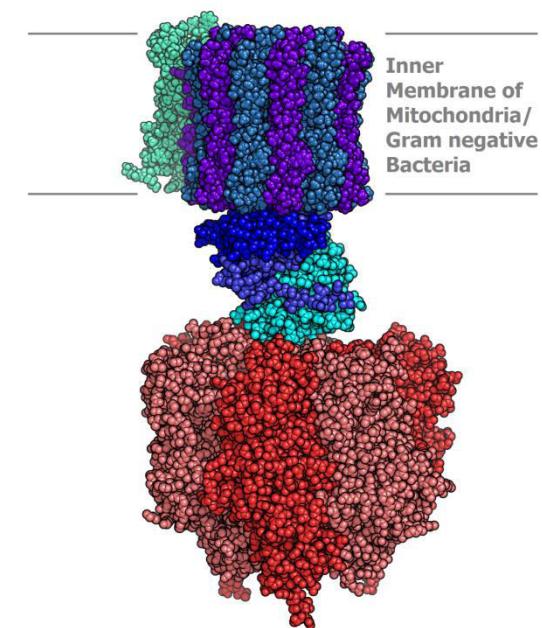
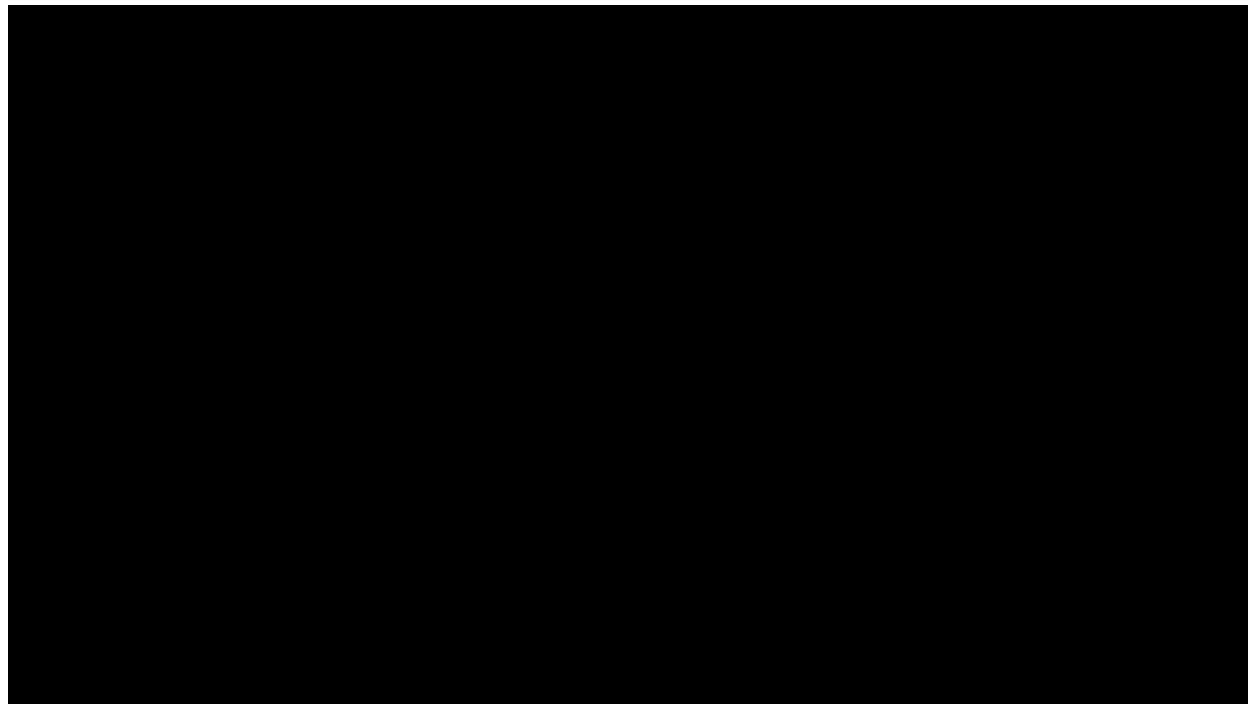
These accelerated protons push on a **rotary mechanical motor**, which converts ADP to ATP (it's a **physical machine**, not what one usually thinks of as "chemistry"!)

About 3 protons need to pass through to charge one ATP (100 charges per second).



# The Proton Gradient

- The ATP synthase machine:



<https://www.youtube.com/watch?v=XI8m6o0gXDY>

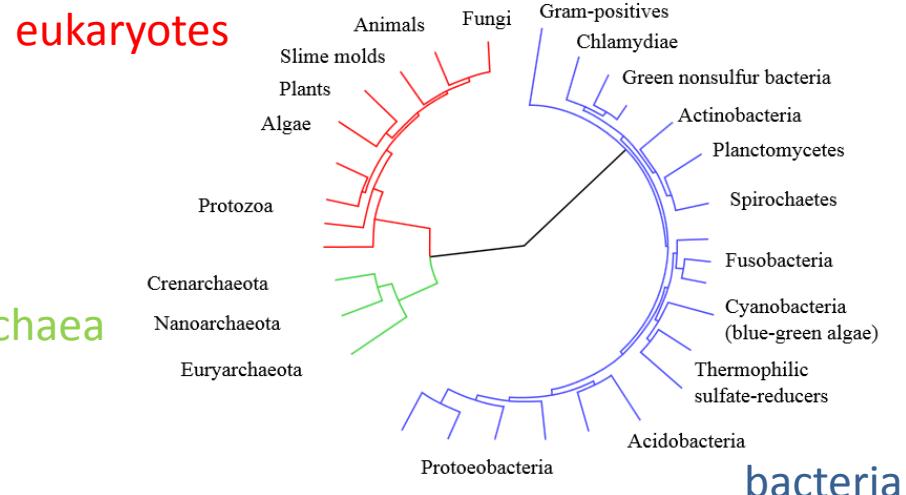
**intelligent design?**

# The Proton Gradient

**proton gradient...so what?**

# The Proton Gradient

- Today, ***all*** energy that living organisms use ultimately comes from **generating and tapping a proton (or other ion) gradient**.
- It is the **universal “battery” that powers all life on Earth**, as universal as the genetic code itself. Thus, it is an important clue to the **origin of life**.
- For example, the **ATP synthase** (the machine that **taps** energy from the gradient) is as **universal** as the **ribosome** (the protein synthesis machine), and it displays the same deep “phylogenetic” split between archaea and bacteria ⇒ **it was archaea present in the last universal common ancestor (LUCA)**, and must have “evolved” prior to this. (How? More later...)

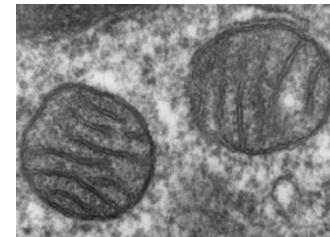


# The Proton Gradient

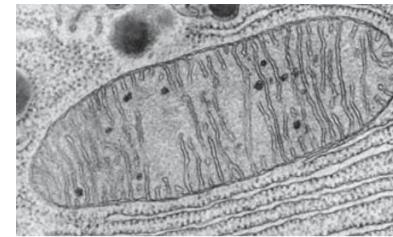
- In eukaryotes (like us), this proton gradient “battery” is inside **mitochondria**. The mitochondria across all eukaryotes have the **same general structure** (see pictures)
- These bacteria-sized organelles may have originally been **aerobic bacteria** that **invaded and colonized** early eukaryotic cells (they have an independent bacteria-like genome!)



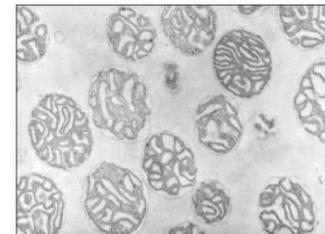
examples of eukaryotes



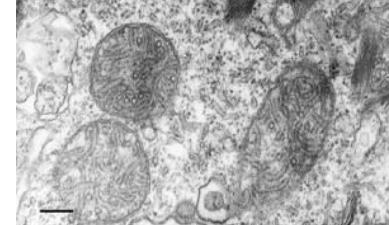
mammalian lung



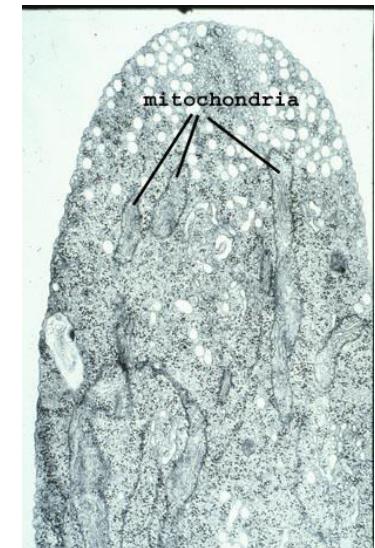
bat pancreas



mung bean



paramecium



fungus

# The Proton Gradient

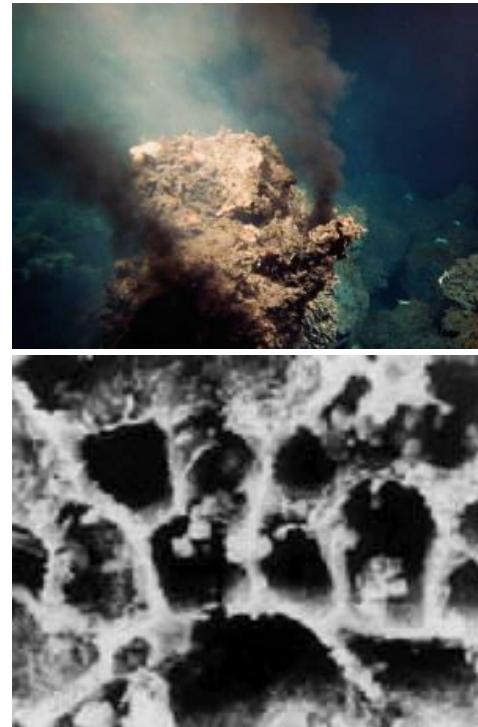
- Okay, so ion gradients are the universal battery of life. But this raises a **severe evolutionary chicken-and-egg problem:**
  - ✓ **Proteins** are used to generate and tap ion gradients (e.g., the ATP synthase is used to tap the proton gradient and convert ADP to ATP)
  - ✓ But **energy** is needed to build proteins (like ATP synthase) in the first place (protein synthesis consumes 75% of a cell's ATP budget)

**Proteins are required to generate energy, but energy is needed to build those proteins.** So where did the energy come from that built the first proteins?

- This has long been a **deep mystery**, but recently progress has been made: **Naturally occurring** proton gradients at **deep-sea hydrothermal vents** have been shown to **spontaneously synthesize amino acids** (building blocks of proteins) and **nucleotides** (building blocks of RNA & DNA), and may have been the **initial spark of life**. We are one step closer to understanding how it **might** have been possible for **rocks to “come to life”!**

# The Proton Gradient

- See: [The Origin of Membrane Bioenergetics](#) (Lane & Martin 2012).  
Also: [Nature News](#). Martin: “There are lots of theories [of the origin of life] but ours is the first to **start with the cell.**” (Most scientists assume that **self-replicating molecules** or proteins came first.)
- Rocks of deep-sea thermal vents contain labyrinths of tiny thin-walled pores, which could have acted as ‘**proto-cells**’, the first life-forms:
  - ✓ **(CO<sub>2</sub>- and H<sup>+</sup>-rich) acidic** ocean water on the outside and **(H<sub>2</sub>- and OH<sup>-</sup>-rich) alkaline** vent water on the inside, separated by a thin mineral (iron sulfide, FeS) wall, sets up a natural proton gradient *of magnitude & orientation used by modern cells*;
  - ✓ Powered by the proton gradient, the FeS wall can **catalyse** conversion of **CO<sub>2</sub>** and **H<sub>2</sub>** into organic carbon-containing molecules, and **concentrate** them inside, enabling them eventually to generate **genes, proteins and a proto-membrane**.



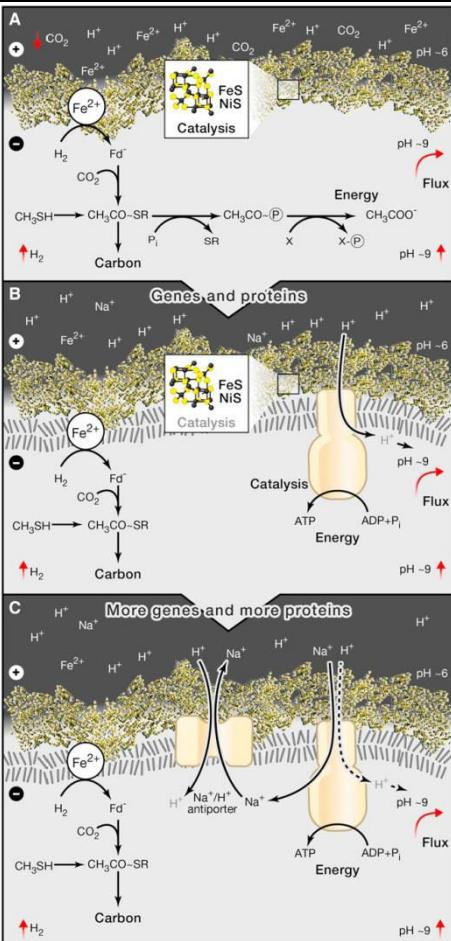
Iron sulphide (FeS) honeycomb: “a fertile environment.”

# The Proton Gradient

Some details are shown in diagrams A and B:

- A. In the presence of the proton gradient, FeS **catalyses**  $\text{CO}_2 + \text{H}_2 \rightarrow \text{Carbon} + \text{Energy}$  ( $\text{CH}_3\text{COO}^- \sim \text{glucose}$ ). **Note:** Modern microbes near vents, that similarly live off  $\text{CO}_2$  and  $\text{H}_2$ , use enzymes (protein catalysts) **also** based on FeS and Fe(Ni)S (a hint this may be right...)
- B. The carbon, plus this relatively **low entropy** energy inside the proto-cell, allows the formation of **complex** organic carbon structures like amino acids, RNA bases, sugars, lipids, and possibly (?) even **ATP synthase** (a very efficient coupling to the proton gradient).  
[Note that the  $\text{H}^+$  (acid) passing through the ATP synthase is neutralized by continuous supply of  $\text{OH}^-$  (base) in the vent water.]

The proto-cell evolves towards **ever more efficient** coupling to the proton gradient, since this increases the rate at which energy is dissipated (and the universe moves to a state of **higher entropy**).



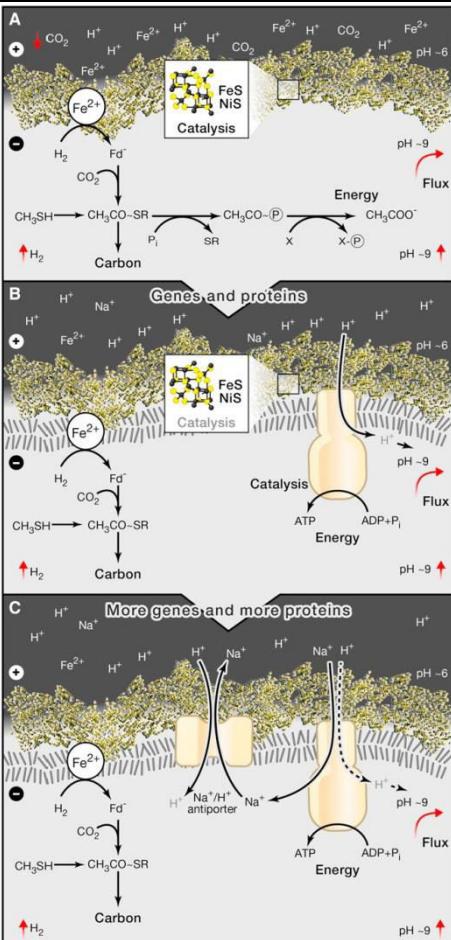
# The Proton Gradient

Such proto-cells could **tap** the naturally occurring proton gradient, but how could they evolve to **generate** their own gradient, and become **free-living** cells, floating around in the ocean?

Three things would be needed:

- ✓ A completely sealed **organic cell wall** (to replace the FeS rock wall)
- ✓ A **proton pump** (to pump out the protons that enter through the ATP synthase, which are no longer neutralized by vent water  $\text{OH}^-$ )
- ✓ An **energy source** to drive the pump

**Idea:** The FeS wall was **leaky** to  $\text{H}^+$ , reducing efficiency. Lipids (fats) may have naturally formed an organic cell wall (more later...), which would help reduce the leakiness, and would **improve efficiency**.



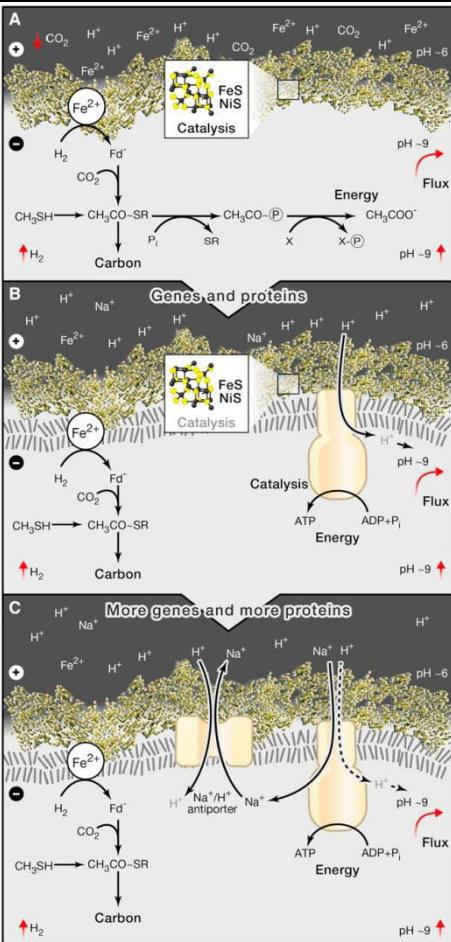
# The Proton Gradient

Assuming the evolving organic cell wall **tightened up slowly**: was **first** impermeable to **large** ions like  $\text{Na}^+$ , then to **small** ions like  $\text{H}^+$  (protons)...

C. ...there would have been a long transition time during which a  $\text{Na}^+$  gradient would have been **more efficient** than a  $\text{H}^+$  gradient. This could explain **why** modern vent microbes have a very simple  $\text{Na}^+/\text{H}^+$  “**antiporter**”, which runs for **free**, converting  **$\text{H}^+$  bioenergetics** to  **$\text{Na}^+$  bioenergetics**. In such a transition-stage proto-cell, the natural proton gradient is still used ( $\text{H}^+$  passing through the antiporter is still neutralized by the continuous supply of  $\text{OH}^-$  in the vent water).

This suggests a **plausible** path to an **organic cell wall** and a  $\text{Na}^+$  pump. What **drives** it? Just switch from proton gradient to **energy from metabolizing  $\text{CO}_2 + \text{H}_2$** . The newly “living” cell could then detach from the rock and become a free-living cell floating in the ocean.

Many details are **still mysterious**, but we are **one step closer!**



# Summary

## Summary:

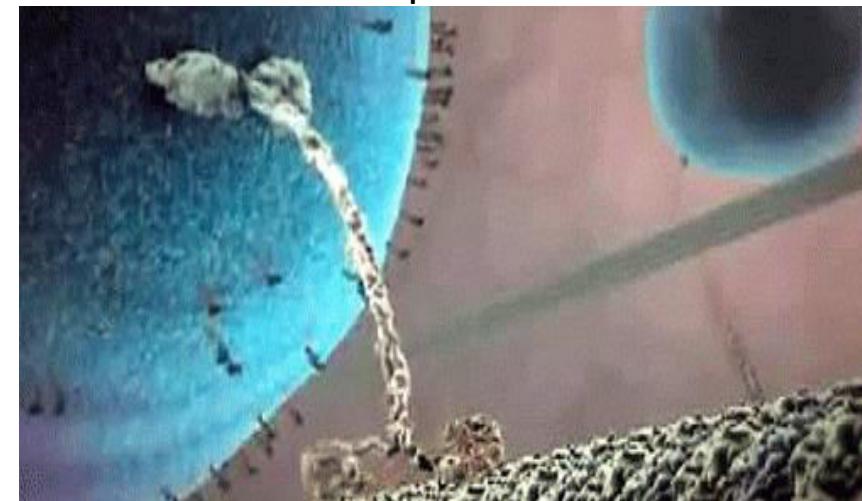
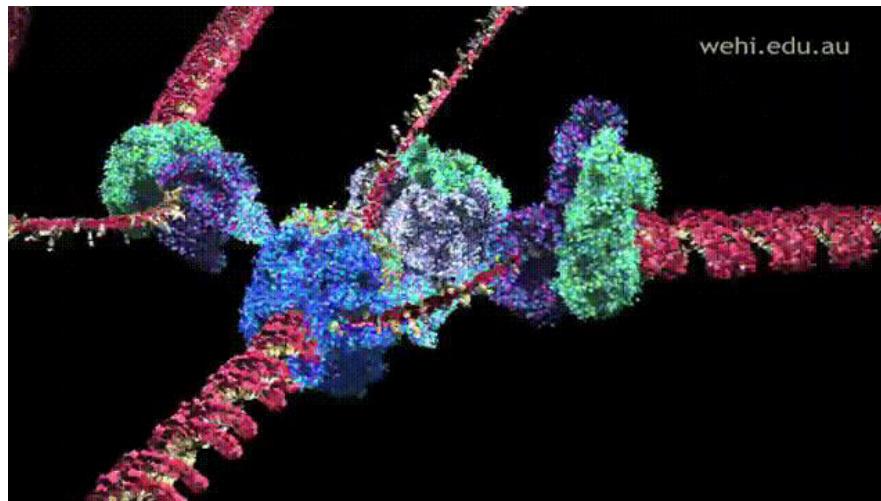
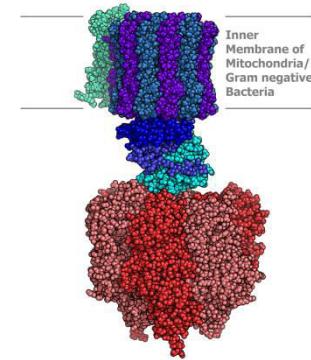
- We **may never be certain** how life on Earth began. The further back we push the question, the less direct evidence survives.
- Nevertheless, scientists are making **stunning progress** towards a variety of possible/plausible ways that life **may** have begun.
- But we still have a long way to go, which is good in the sense that **science thrives on mystery**, and **dies as knowledge becomes complete**.

# The Real Question

**Problem:** all of these scenarios rely on complex machines, e.g., ATP synthase, protein synthesis machinery, DNA replication machinery, etc.

So the **REAL QUESTION** is:

How might such complex machinery have arisen spontaneously?

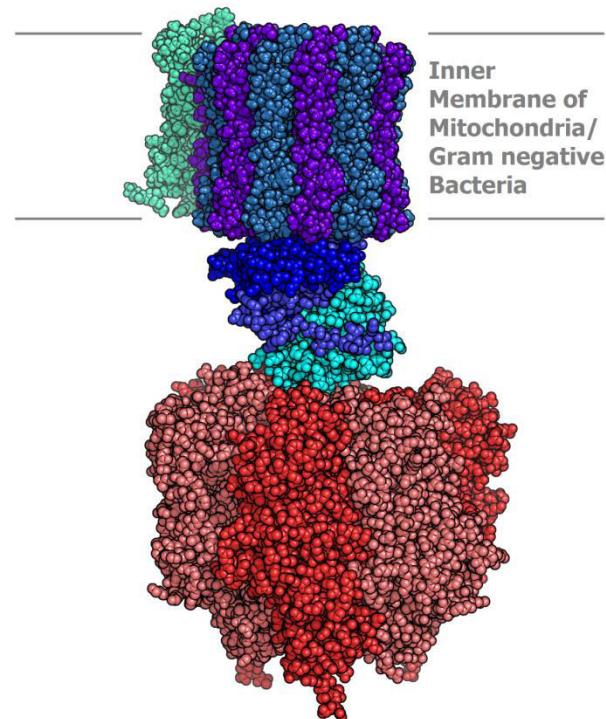


kinesin protein

# The Real Question

## Recall:

- Physicists have discovered two fundamental laws of nature:
  - ✓ 1<sup>st</sup> Law: **Quantity** of energy is **constant**
  - ✓ 2<sup>nd</sup> Law: **Quality** of energy **continually decreases**
- We have shown that life is **consistent** with these basic thermodynamic laws.
- But can thermodynamics explain **why** life should arise in the first place? **How** its complex machinery evolved **spontaneously?** *This* is the sort of explanation of the origin of life scientists would like to have!



# The Real Question

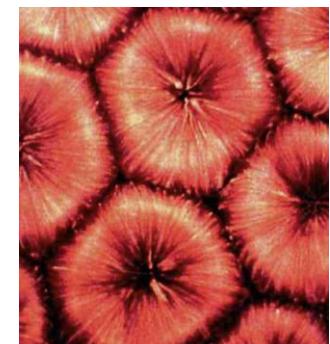
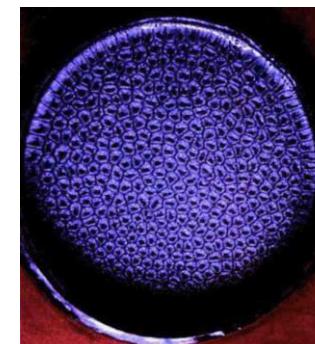
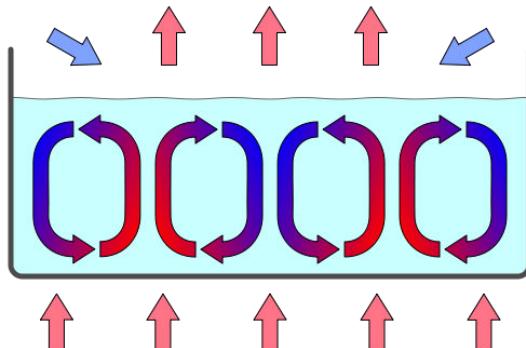
The problem is:

- Thermodynamics was originally the study of **closed systems** at or near **equilibrium**.
- But living organisms are:
  - ✓ **NOT closed systems:** They *exchange* matter and energy with their environment
  - ✓ **NOT in equilibrium:** They are continually *changing*, animated, not static
- Lane: “Cells require **dynamic disequilibrium**—that is what being alive is all about.”



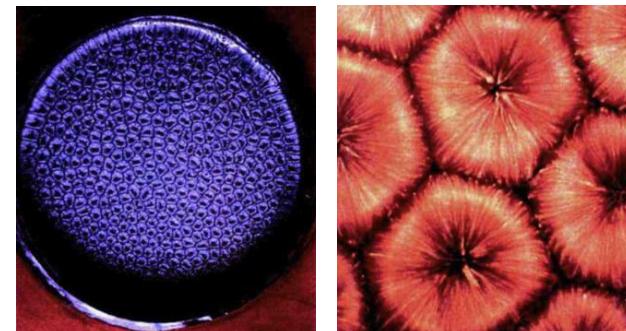
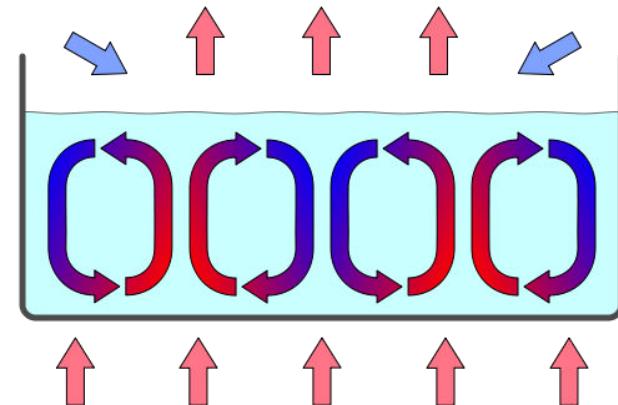
# Dissipative Structures

- Late 1960s–early 1970s: Ilya Prigogine ([1977 Nobel Prize](#)) discovered **dissipative structures** in systems that are:
  - ✓ **Open:** they have energy (or matter) **flowing through them**
  - ✓ **Non-equilibrium:** *Steady state*, but *not static* (flow = motion)
- Example: **boiling water** (or other **convection cell** structures)



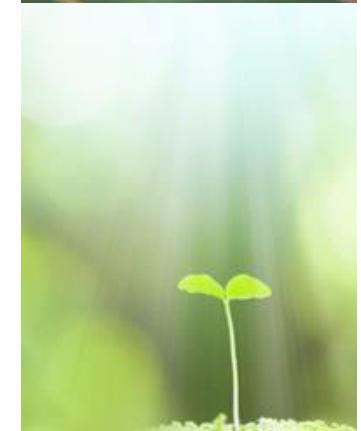
# Dissipative Structures

- Energy flows through the system:  $Q_{\text{in}} = Q_{\text{out}}$
- But:  $T_{\text{in}} > T_{\text{out}} \Rightarrow$  entropy increase of the cold sink is greater than the entropy decrease of the hot source: entropy of universe is increasing (at a certain rate)
- Energy is first carried by conduction. But above a critical  $\Delta T$ , convection sets in (non-equilibrium): an ordered structure of *Bénard* cells spontaneously appears:
  - ✓ This ordered structure increases the energy flow & dissipation rate, increasing entropy generation rate
  - ✓ This allows the system (like life) to be in a state of lower entropy, i.e., more ordered form (cells)
  - ✓ Energy must continually flow and be dissipated (degraded); when it stops, the structure “dies”



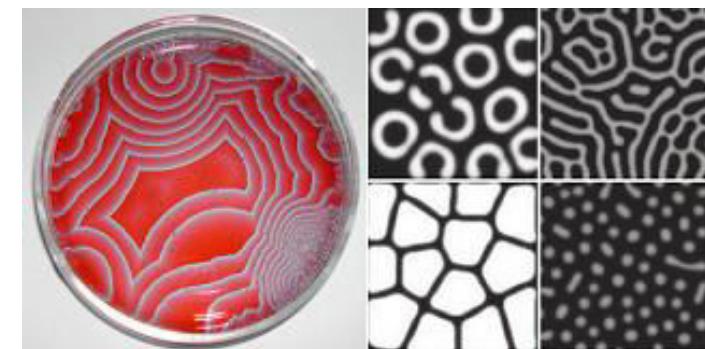
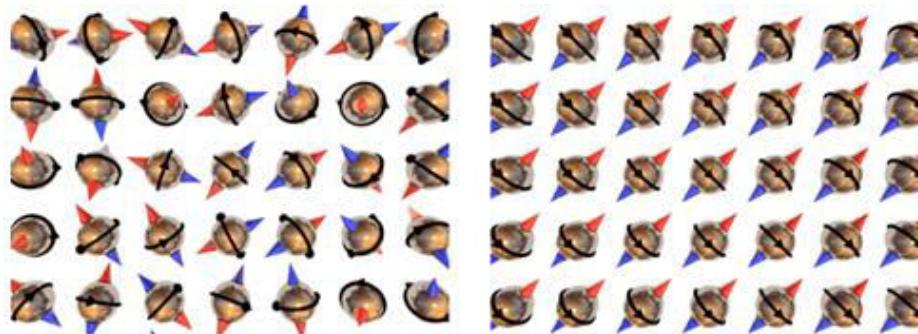
# Dissipative Structures

- This is *analogous* to a living organism:
  - ✓ An **open** system with energy/matter **flowing** through it (sunlight, food, etc.), operating **out of thermodynamic equilibrium**
  - ✓  $E_{\text{in}}$  (sunlight, food) =  $E_{\text{out}}$  (body heat, waste), but the **quality** of the energy is **degraded** ⇒ entropy of universe **increases** (at some **rate**)
  - ✓ This **external entropy production** is what allows the system to maintain a state of relatively **low internal entropy** (high order)
  - ✓ The system survives only while energy is being **dissipated** (dispersed, degraded). When it **stops**, the organism (ordered structure) **dies**.
- ...*analogous*, yes, but life is a **much richer** phenomenon. **But it's a start!**



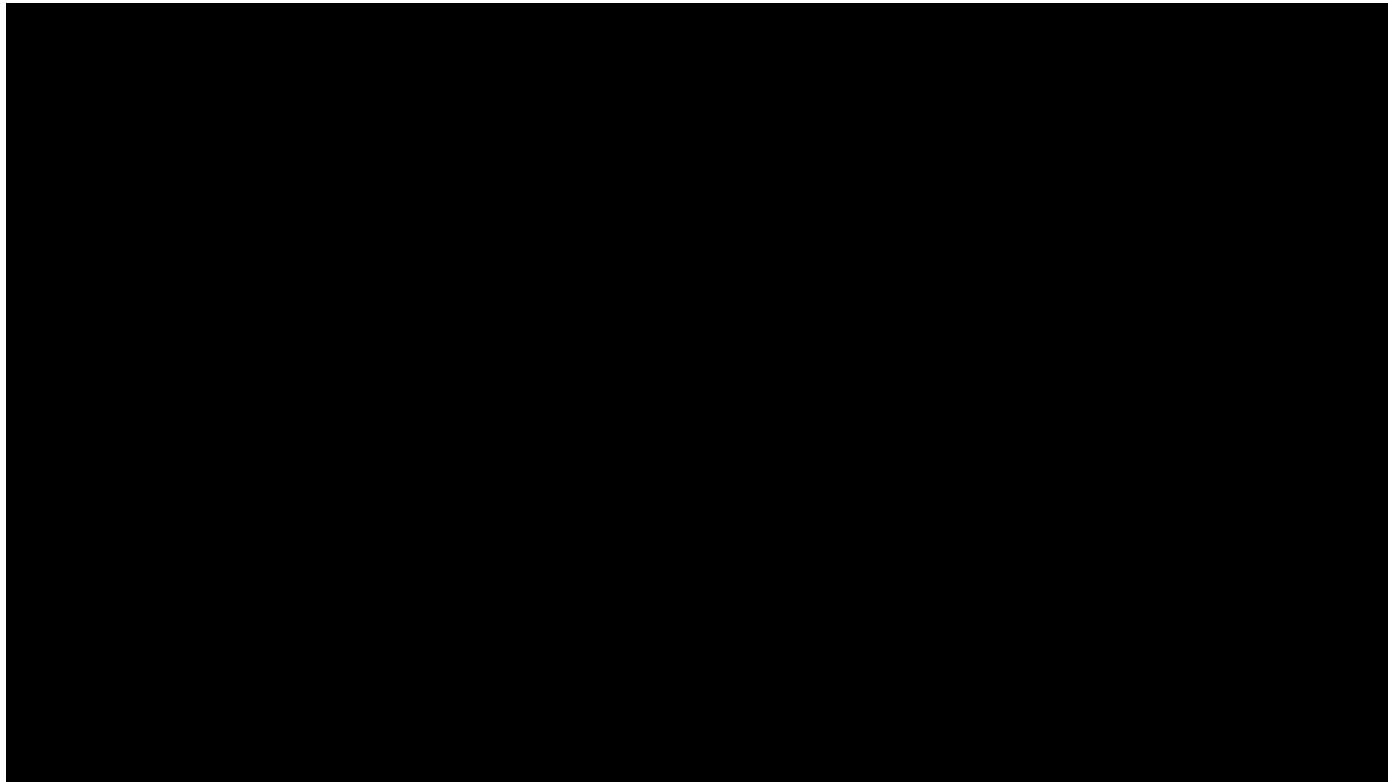
# Self-Organization

- **Dissipative structures** are related to **self-organizing** systems: order arises out of the local interactions between smaller component parts of an initially disordered system.
- **Many** examples of this general phenomenon:
  - Physics: Spontaneous magnetization
  - Chemistry: Oscillating & reaction-diffusion reactions
  - Biology: Birds flocking, fish schooling, etc.



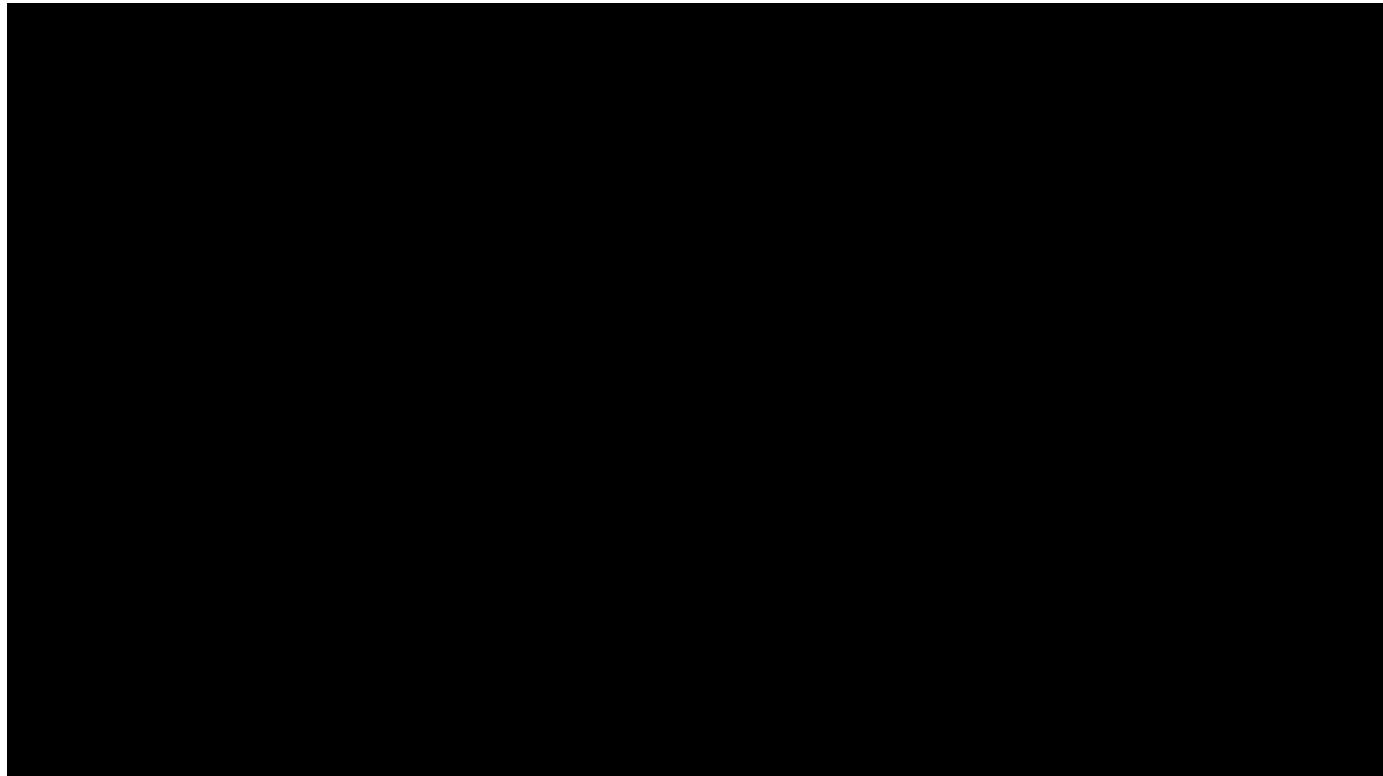
# Self-Organization

- Biology: Spontaneous protein folding



# Self-Organization

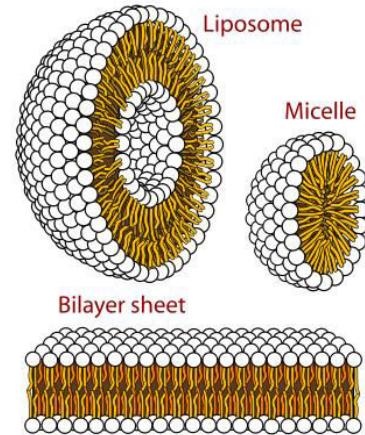
- Biology: Spontaneous formation of lipid bilayers



# Self-Organization

- Biology: Spontaneous formation of lipid bilayers

- ✓ The cell membranes of **almost all living organisms** are made of a lipid bilayer (including organelles inside the cell)
- ✓ Recall: the **hydrophobic tails** point inward to avoid contact with the water. The resulting cell membrane is highly structured, but it is **less ordered (higher entropy)** than when the tails are in water, because that requires very low entropy water molecule “cages”
- ✓ The self-assembly is **driven** by random thermal jostling by the environment, which allows the system to **explore nearby configurations**, finding ones that **maximize total entropy** (minimize total free energy), that get “locked in” when the available energy disperses into the environment



## Deeper Understanding of the Second Law

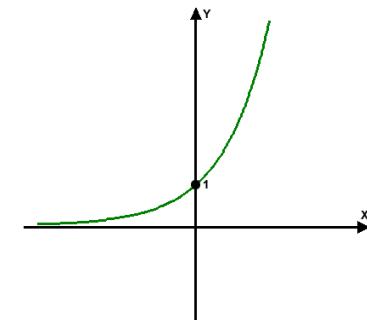
- 1994: Denis Evans & Debra Searles proved:

✓ The Second Law ( $\Delta S \geq 0$ ) is **not** strictly true. In **microscopic** systems, the entropy of an isolated system can **fluctuate**, mostly increasing, but sometimes **decreasing**. This has been observed in experiments.

✓ Roughly speaking, the **fluctuation theorem** states:

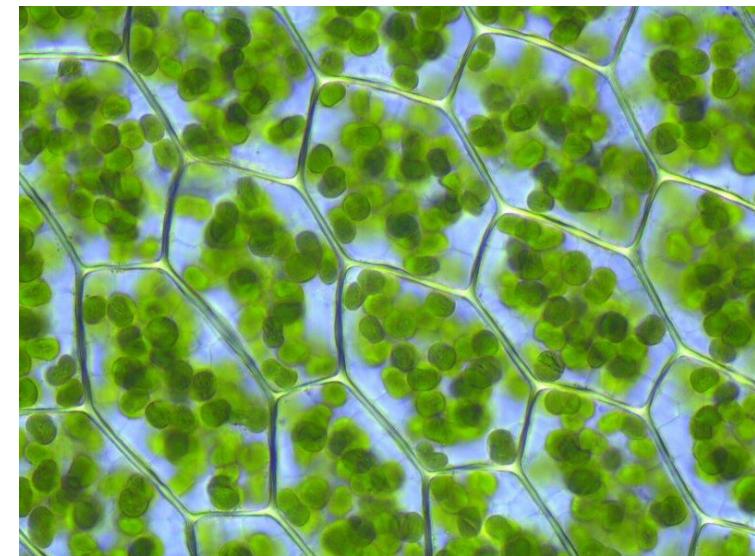
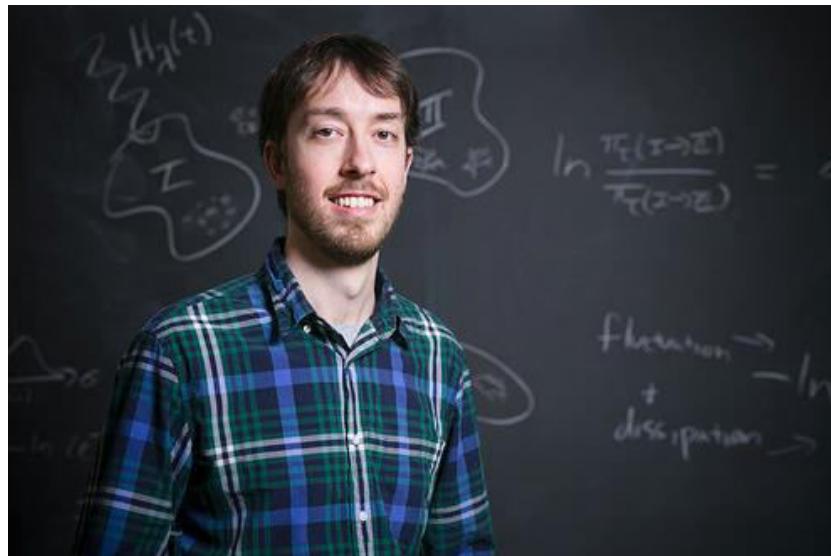
$$\frac{\text{Probability}(+\Delta S)}{\text{Probability}(-\Delta S)} = e^{\Delta S}$$

- ✓ In words:
- **Small** fluctuations are **equally likely** to be **positive or negative**
  - **Large** fluctuations are **almost always positive**
- ✓ ...but **on average**, the Second Law **is** strictly true:  $\langle \Delta S \rangle \geq 0$ .



## Deeper Understanding of the Second Law

- 1999: Gavin Crooks [proved](#) a **generalization** of the fluctuation theorem...
- 2013–2015: Jeremy England, a **biophysicist at MIT**, has applied the above to **living organisms** in “[Statistical Physics of Self-Replication](#)” and “[Dissipative Adaptation in Driven Self-Assembly](#)”. See also: [Quanta Magazine](#) & [Nature Physics](#) & [Talk](#) & [Radio](#)

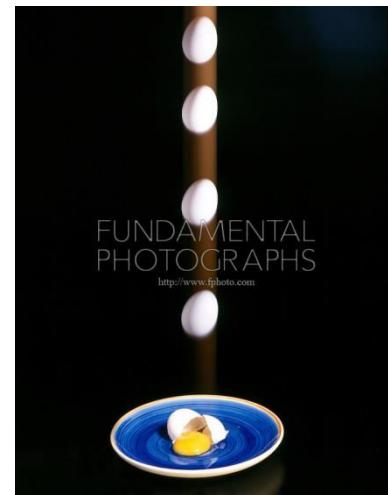


# Why is there life?

- In doing so, England may be close to answering the question “**Why is there life?**”
- **Important:** Some of this is still **speculative**, not fact; it is a good example of **science in action**:
  - ✓ There are **skeptics** (important in science!): “Jeremy’s ideas are interesting and potentially promising, but at this point are extremely speculative, especially as applied to life phenomena”—Eugene Shakhnovich (chemistry professor at Harvard)
  - ✓ But there is also **great excitement**:
    - “[England has taken] a very brave and very important step...the ‘big hope’ is that he has identified the underlying physical principle driving the origin and evolution of life”—Alexander Grosberg (physics professor at NYU)
    - “As an organizing lens, I think he has a fabulous idea. Right or wrong, it’s going to be very much worth the investigation [in her lab]”—Mara Prentiss (physics professor at Harvard)

# Why is there life?

- Basic Idea:
  - ✓ Like smashing an egg, cell replication (and other cell processes) are obviously **irreversible**. But **irreversibility** and **increase in entropy** are intimately connected, so thermodynamics **should** be able to tell us something about life.
  - ✓ But living organisms are **far-from-equilibrium** systems interacting with their environment, and **strongly driven** by external sources of energy (e.g., plant blasted with sunlight). Before work like Crooks', and others, physicists didn't have the mathematical tools to understand such systems. **Now they do.**



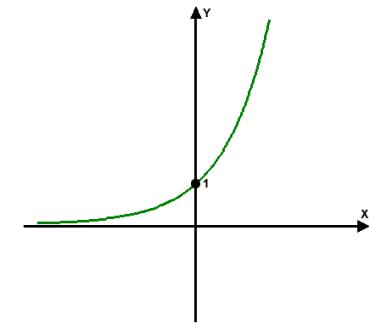
# Why is there life?

- The Physics/Mathematics:

- ✓ Roughly speaking: England took Crooks' **microscopic** formula and figured out its consequences for **macroscopic** things, and discovered a **generalization** of the Second Law, that applies even for systems **driven far from equilibrium** by **energy flows**:

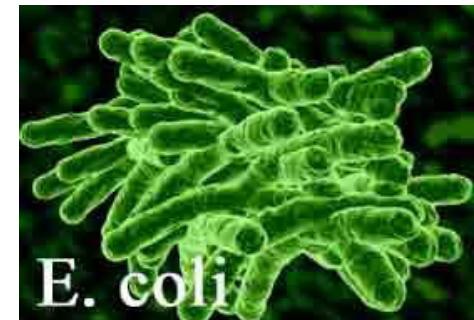
$$\frac{\text{Probability(Forward)}}{\text{Probability(Reverse)}} = \langle e^{\Delta S} \rangle$$

- ✓ It says: The **more irreversible** a spontaneous process is (e.g., cell division), the **more it increases the entropy** of the universe.
- ✓ Or: The **most probable** outcomes are the ones that, on the way to getting there, **increase the entropy of the universe the most**



# Why is there life?

- Analysing the new equation gives a key new insight:
  - ✓ Other things being equal, the better a **driven** system can **absorb and dissipate** energy from that driving force (sunlight, food), the better it is able to do highly irreversible things like cell division.
  - ✓ England has applied the idea to predict the amount of dissipation that should occur during **self-replication of RNA molecules** and **E. coli bacteria**. England: “A great way of dissipating more is to make more copies of yourself.”
  - ✓ England: “Thus, the empirical, biological fact that reproductive fitness is intimately linked to efficient metabolism now has a clear and simple basis in physics.”

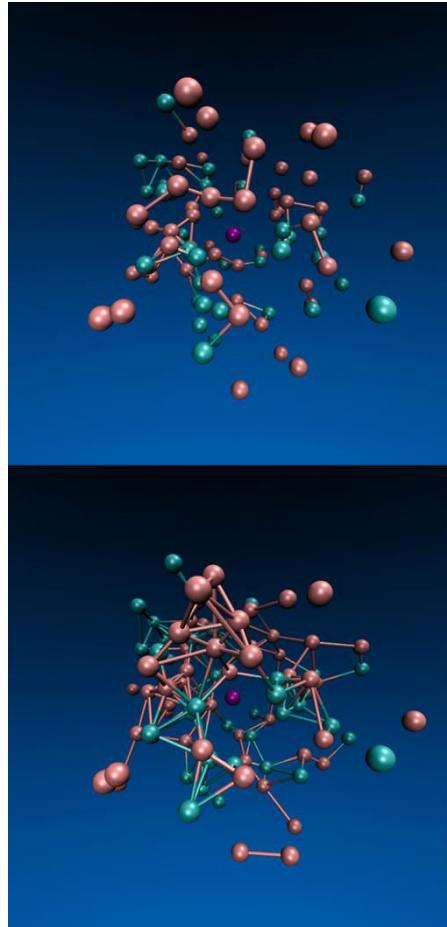


# Why is there life?

- Speculation: “[Dissipation-Driven Adaptation of Matter](#)”

✓ A deeper analysis of the new equation **suggests** that “...clumps of atoms surrounded by a **bath** at some temperature, like the atmosphere or the ocean, should tend over time to **arrange themselves to resonate better** and better with the sources of mechanical, electromagnetic or chemical work in their environments [**driving forces**].”

✓ **Analogy:** the length of the ropes of a swing will **spontaneously** adjust themselves so the **natural frequency** of the swing matches the **driving frequency**, allowing the swing to absorb (and later dissipate) the most energy (!)

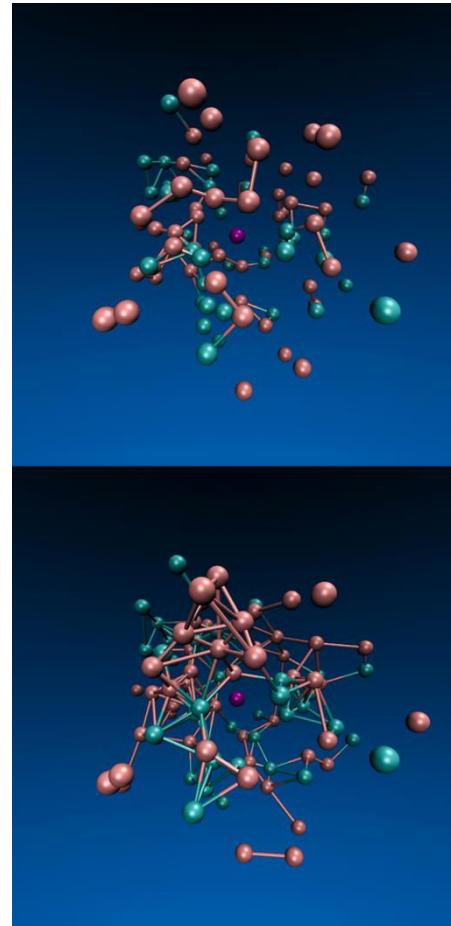


# Why is there life?

- Speculation: “[Dissipation-Driven Adaptation of Matter](#)”

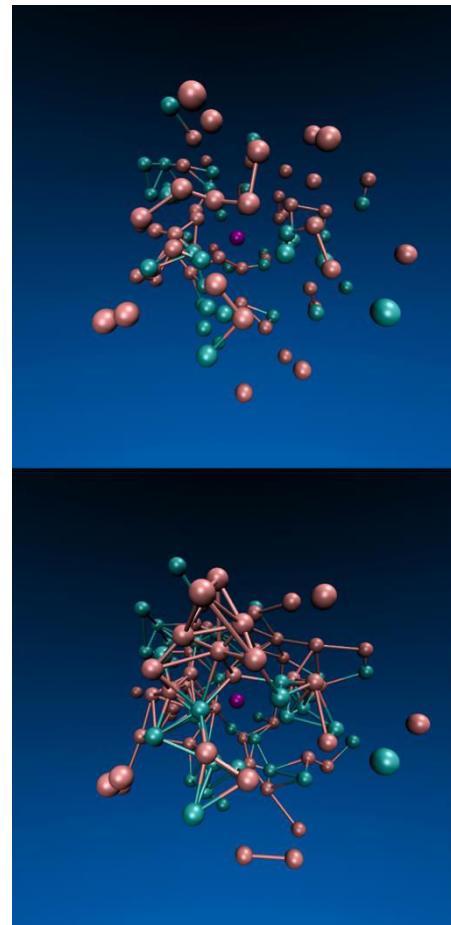
✓ Why is this **plausible**?

1. Alone, thermal jostling of the atoms is not enough to change their configuration (atomic bonds are hard to change).
2. But a periodic driving force (like pushing a swing) can help the thermal jostling make configuration changes happen.
3. After a change, if the additional energy absorbed from the driving force is dissipated as heat into the environment, it is not available to help the system go back, like a ratchet. So **irreversibility is connected to dissipation (entropy increase)**.



# Why is there life?

- Speculation: “[Dissipation-Driven Adaptation of Matter](#)”
  - ✓ Why is this **plausible**?
  - 4. While configuration changes are **mostly random**, the **most irreversible** (or **durable**) changes are those that happen when the system, at that moment, happens to be **better** at absorbing and dissipating energy from the driving force.
  - 5. As time passes, these **less erasable** changes **accumulate**, like a ratchet, shifting the system preferentially in the direction of **better absorption and dissipation**.
  - 6. After a long time, it looks like the system has **self-organized** into a state that is '**well adapted**' to its environment.

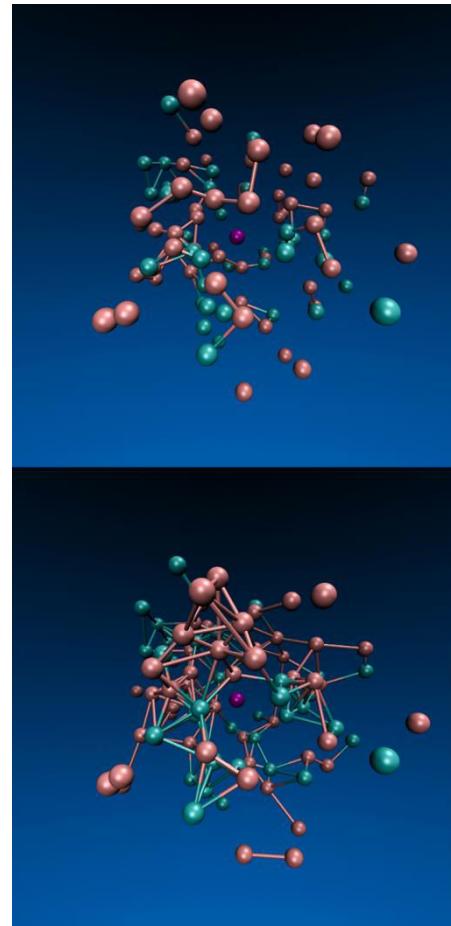


# Why is there life?

- Speculation: “[Dissipation-Driven Adaptation of Matter](#)”

✓ This idea is starting to be tested:

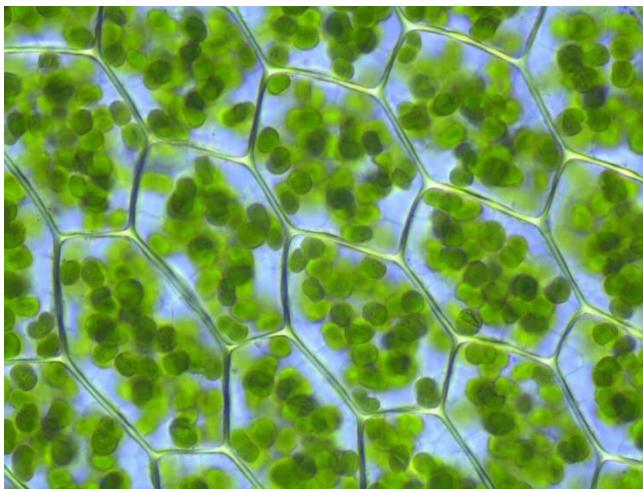
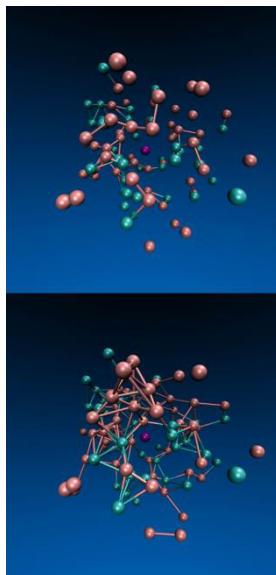
- England has run **computer simulations** of a **random clump** of toy atoms, driven at some frequency.
- Result: “...we do indeed see **emergent ‘adaptive’ resonance** of our system...”, supporting the hypothesis that “...**organized, kinetically stable structures emerge** and persist because their formation is reliably accompanied by extra work absorption and dissipation”.
- “There may be many examples of ‘well-adapted’ structures that did not have parents.” (**Non-Darwinian adaptation...**)



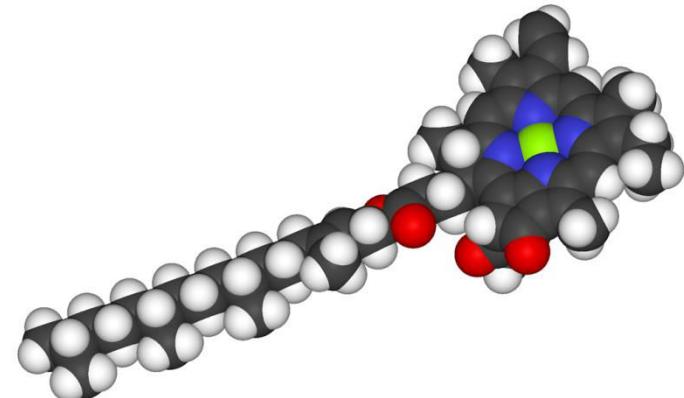
# Why is there life?

- Example: Plants/Photosynthesis

✓ England: “**You start with a random clump of atoms, and if you shine light on it for long enough, it should not be so surprising that you get a plant.**”



Chloroplasts in plant cells

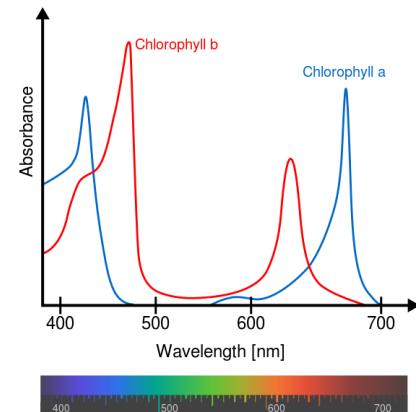
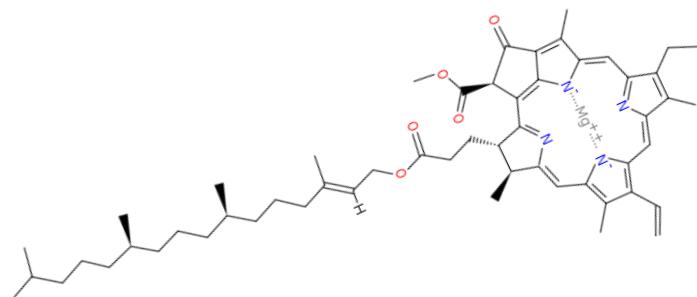
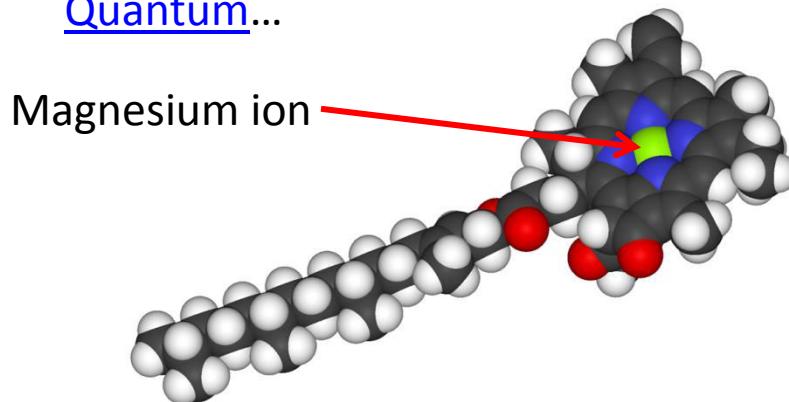


Chlorophyll molecule  
inside chloroplast

# Why is there life?

- Example: Plants/Photosynthesis

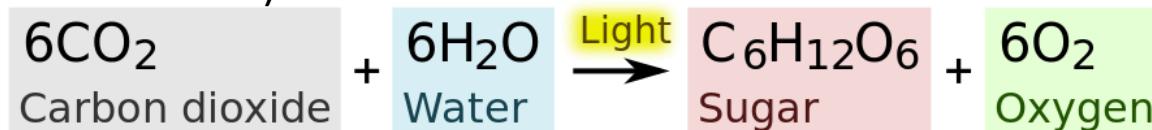
✓ The **chlorin ring** is a simple ring of molecules with  $Mg^{++}$  at the center, of exactly the right size and shape (“length of swing”) to **resonate** with photons (electromagnetic waves from the Sun that “push the swing”) of two different **frequencies** (colours): red and blue. These are **absorbed and dissipated** (but green photons are not, which is why leaves are green).  
Quantum...



# Why is there life?

- Example: Plants/Photosynthesis

- ✓ Ultimately, the **energy absorbed** from the photons is used to **generate a proton gradient** across the **chloroplast membrane**; an **ATP synthase** is used to **tap** the gradient and “**charge**” ADP molecules to ATP, which then carry the energy to all the cells.
  - ✓ This energy is used to make sugar and oxygen (and power other cell functions):

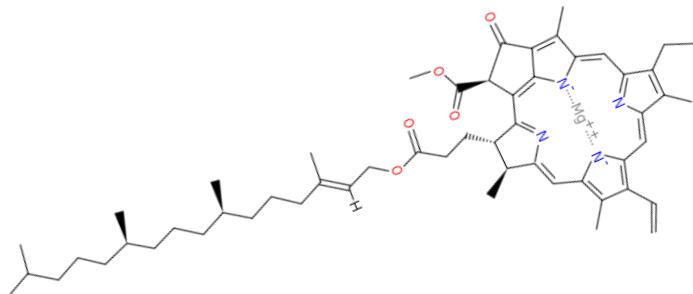
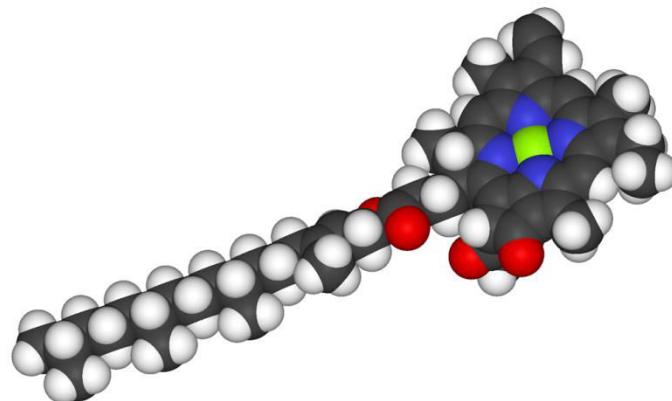


- ✓ The rest is **dissipated in the environment** as waste heat. This is crucial: The resulting **increase** in entropy of the environment is precisely what allows the plant to build and maintain **low entropy structures** (like the chlorin ring).

# Why is there life?

- Example: Plants/Photosynthesis

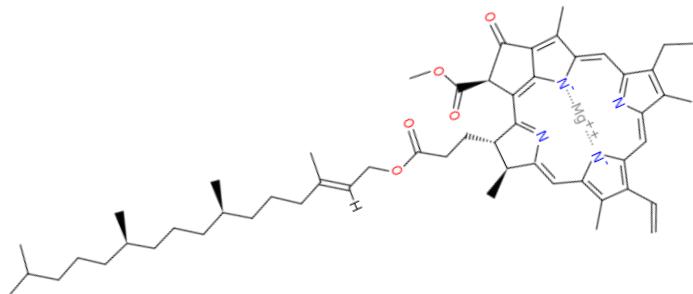
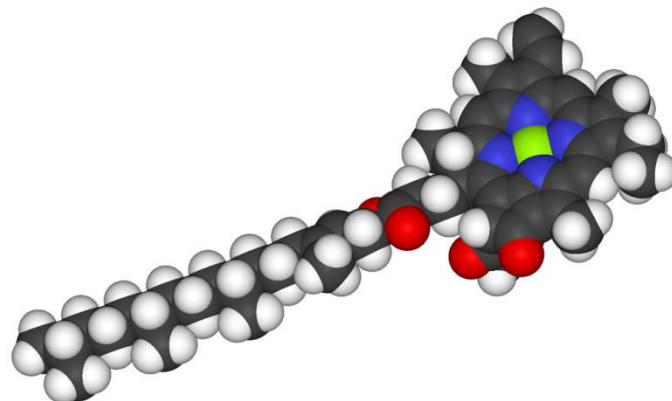
✓ Could the **chlorin ring** be an example of an **ordered structure** that **spontaneously evolved** by “dissipation-driven adaptation of matter” to allow photosynthetic organisms to harness (and dissipate) more energy from the Sun? (Speculation!!)



# Why is there life?

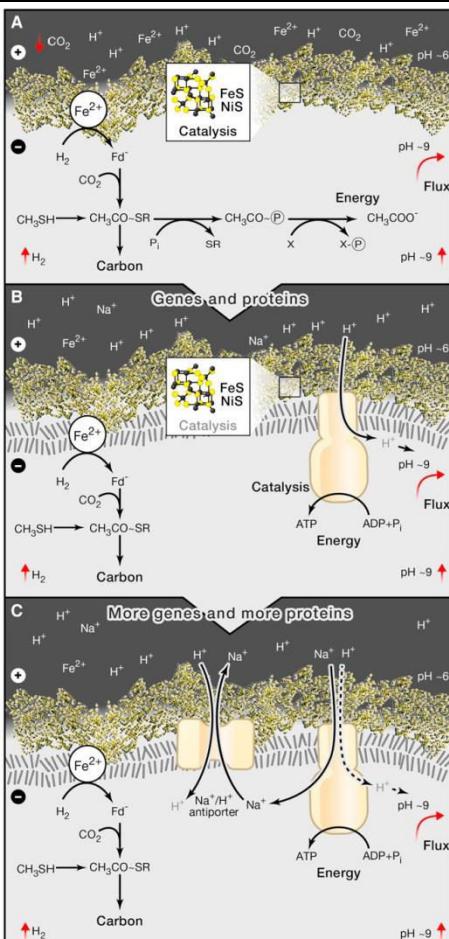
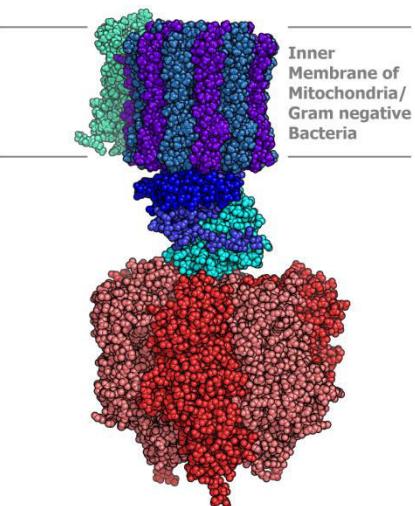
- Example: Plants/Photosynthesis

✓ [Recent experiments](#) (Ito et al, 2013) have shown that, in the presence of light of a given frequency, silver nanorods will **spontaneously self-assemble** into a ring-like structure that **resonates at that frequency**, to best absorb (and dissipate) the energy in the light.



# Why is there life?

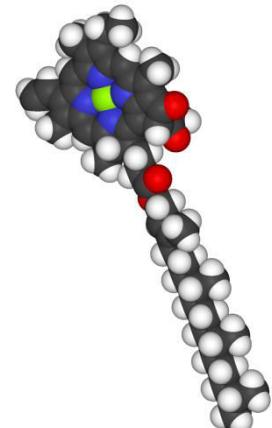
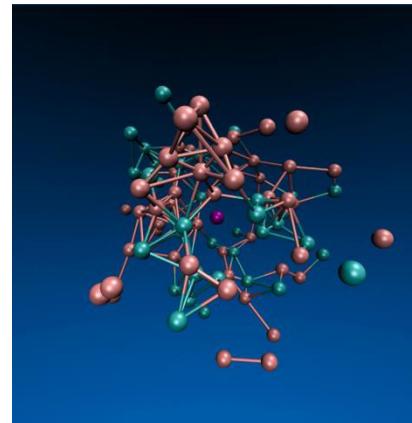
- Could the **ATP synthase** be another (more complex) example of an ordered structure that **spontaneously evolved** by “dissipation-driven adaptation of matter” to allow proto-cells to harness (and dissipate) more energy from the natural proton gradient near deep-sea hydrothermal vents? (Speculation!!)



# Why is there life?

- Application to Evolution & Origin of Life:

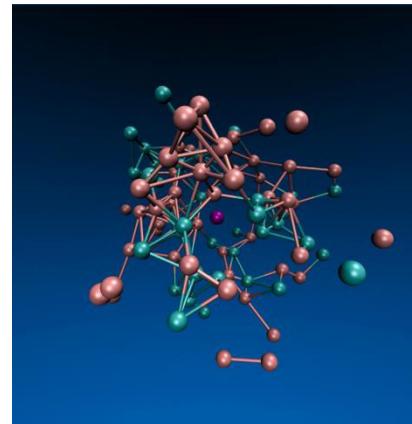
- ✓ Darwinian evolution explains how life evolved **after it began**, but not **how it began**. If correct, “**dissipation-driven adaptation of matter**” might explain **both**. England: “from the perspective of the physics, you might call Darwinian evolution a special case of a more general phenomenon.”
- ✓ Key new idea is **adaptation without replication**: Dissipation-driven adaptation could have **spontaneously** evolved structures that got better and better at **eating energy** in the environment, e.g., the chlorin ring that eats sunlight.
- ✓ Such structures would then be available in the “pre-biotic soup” as building blocks for yet more complex structures, and eventually replicating life. It didn’t have to happen “suddenly”.



# Why is there life?

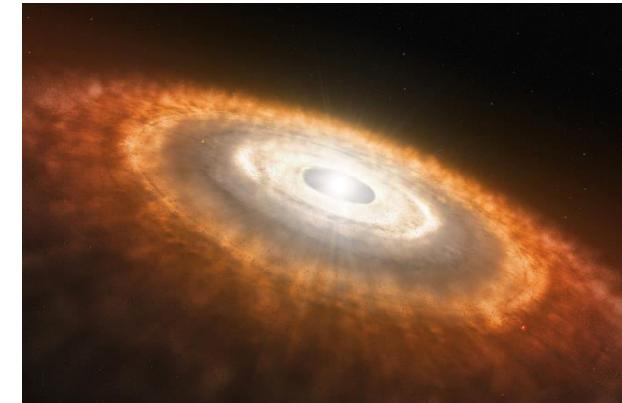
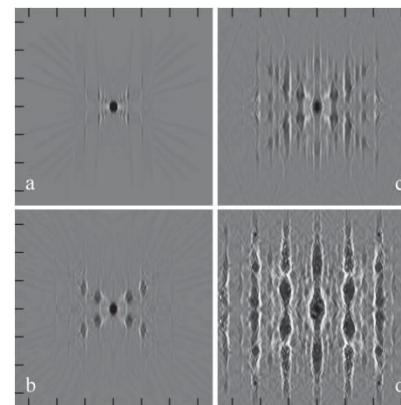
- Application to Evolution & Origin of Life:

- ✓ **Replication itself** may be understood under the **same** umbrella of dissipation-driven adaptation. Recall England: “A great way of dissipating more is to make more copies of yourself.”
- ✓ England: “Under the right circumstances, which aren’t rare at all, matter **tends naturally** toward greater organization, complex structures and adaptive behavior, **making life a likely, even inevitable result of physics.**”
- ✓ This is arguably plausible, but still highly speculative. It’s exciting, though, because it **might** explain, for very general reasons tied to the basic physics of the universe, **why there is life!**



# Why is there life?

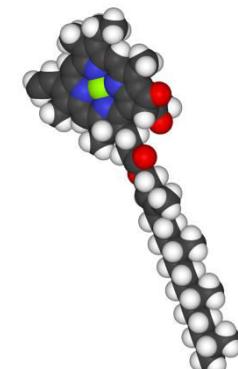
- Applications Beyond Life:
- ✓ Dissipation-driven adaptation of matter may underlie **many physical phenomena**, ranging from snowflakes and sand dunes, to self-replicating vortices in the protoplanetary disk.
- ✓ **The point is:** The transition from non-living matter to living matter may not be such a big leap.



Vortices in a shear flow **spontaneously replicate** by absorbing energy from the surrounding fluid. This has applications to “dead zones” in protoplanetary disks, and may play a role in star and planet formation.

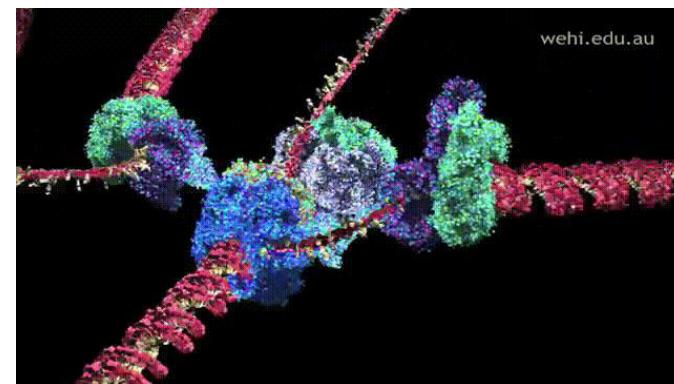
# Summary: Dissipation-Driven Adaptation of Matter

- **Dissipation-driven adaptation of matter** suggests that a random system of particles in a heat bath, driven out of equilibrium by an external energy source, may **spontaneously** create **ordered structures** that allow it to better absorb (and ultimately **dissipate**) that energy.
- **Why?** The heat bath “jostles” the particles around, allowing them to **explore** many configurations. The external energy source **biases** configuration changes, ratcheting towards structures that better **resonate** with the energy source—better at ‘eating’ the energy.
- While **still speculative**, there is reason to hope that it may be a fundamental principle behind a wide range of phenomena in nature, including possibly the **origin and evolution of life**. It’s a promising idea that helps scientists focus attention in a potentially fruitful direction. But of course **it might be wrong...**



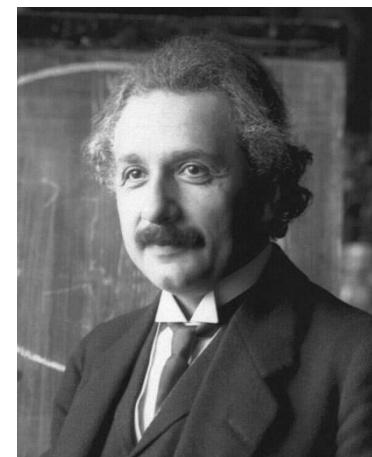
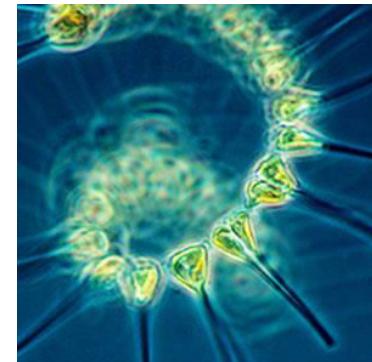
# Summary: The Importance of Thermodynamics

- **Origin & Evolution of Life?** Biology → Chemistry → Physics:
  - ✓ It's a BIG question, and all of the sciences play an important role
  - ✓ Obviously, Biology leads the way. But Chemistry becomes crucial as the questioning moves to ever smaller scales ("molecular biology")
  - ✓ Physics is the most "fundamental" of the three sciences. As such, we'd expect its main contribution to be very simple and overarching, e.g., "**Life may be an inevitable consequence of thermodynamics (?)**"



# Summary: The Importance of Thermodynamics

- Comments on thermodynamics:
  - ✓ Living organisms are many-particle systems immersed in a heat bath, driven out of equilibrium by the matter and energy they exchange with their environment. **This is precisely the subject of non-equilibrium thermodynamics.** The recent improvements in our physical/mathematical understanding of this branch of physics seems bound to impact our understanding of life.
  - ✓ **Einstein:** “A theory is the more impressive the greater the simplicity of its premises is, the more different kinds of things it relates, and the more extended is its area of applicability. Therefore the deep impression which classical thermodynamics made upon me. It is the only physical theory of universal content concerning which I am convinced that within the framework of the applicability of its basic concepts, it will never be overthrown.”



# Summary: The Importance of Thermodynamics

- Comments on thermodynamics:
  - ✓ The application of thermodynamics has, in the past, led to profound shifts in our understanding of the world:
  - The application of thermodynamics to understand the colour spectrum of **hot objects** sparked the discovery of the **quantum nature** of the universe
  - The application of thermodynamics to **black hole entropy** sparked the first concrete step towards a **unified theory of quantum gravity**
  - It wouldn't be surprising if the application of thermodynamics to the phenomenon of life provides important new insights...



# Epilogue: Life and Thermodynamics

Back to: **Why do we eat?**

- To get **energy**!
- But by the 1<sup>st</sup> law of thermodynamics, energy cannot be created or destroyed. We cannot “use” energy or “waste” energy. Assuming a steady state, the biosphere **does not consume energy**: energy in = energy out.
- But energy can be **degraded**. Life takes in **high-quality/low-entropy** energy (chemical or sunlight) and excretes **low-quality/high-entropy** energy (heat and waste). This high entropy excretion is what allows living organisms to maintain their relatively low entropy structure.



# Epilogue: Life and Thermodynamics

Back to: **Why do we eat?**

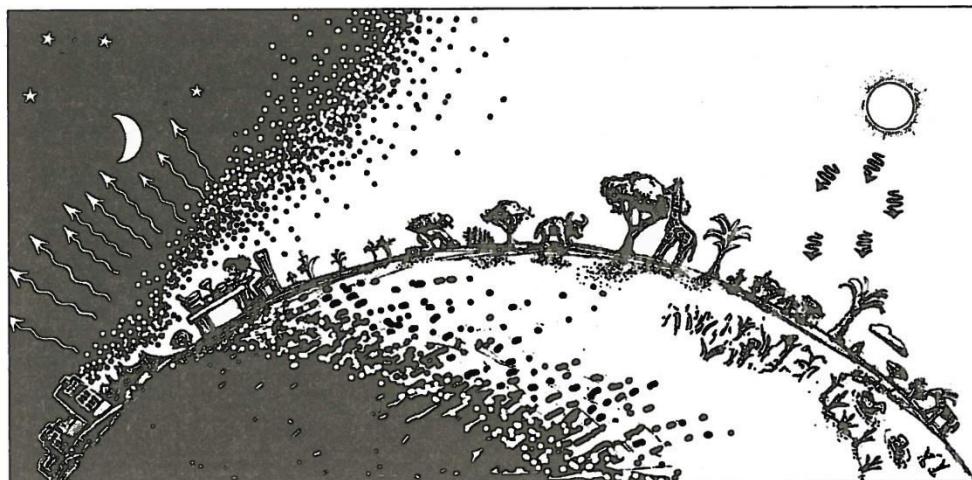
- So more correctly, life consumes **free energy** ( $F = U - TS$ ). Energy will never run out. It is eternal. It is *free energy* that the universe is running out of, as total entropy inexorably increases. (Roughly speaking, total  $U$  does not change, but total  $S$  will continue to increase until  $F = 0$ . Then no life.)
- Where does this free energy **come from**? There are **two sources**:
  - ✓ The **Sun** (or other stars in the case of extra-terrestrial life)
  - ✓ The **Earth** (chemical and thermal **disequilibrium** of a planet)



# Epilogue: Life and Thermodynamics

## Example: Free energy from the Sun

- ✓ The Earth absorbs **high energy** (hot) photons from the Sun, warming its surface
- ✓ On average, the Earth **does not get hotter** (notwithstanding global warming, etc.)
- ✓ Thus, the Earth must radiate exactly the same amount of energy back into space, but now in the form of **lower energy** (cooler) photons (infrared)

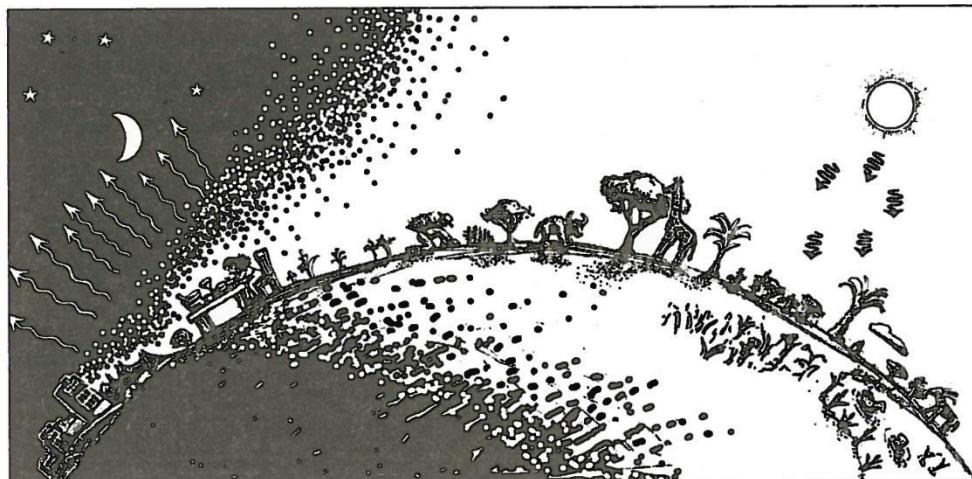


Picture from Roger Penrose's  
*Cycles of Time: An Extraordinary  
New View of the Universe*

# Epilogue: Life and Thermodynamics

## Example: Free energy from the Sun

- ✓ Since energy in = energy out, there must be **many cooler photons** radiated back into **cold space** for each **hot photon from the Sun**.
- ✓ More photons = more ways of dispersing the same energy = higher entropy. Like life itself, the Earth takes in **high-quality/low-entropy** energy from the Sun and expels the same amount of energy, but now as **low-quality/high-entropy** energy.

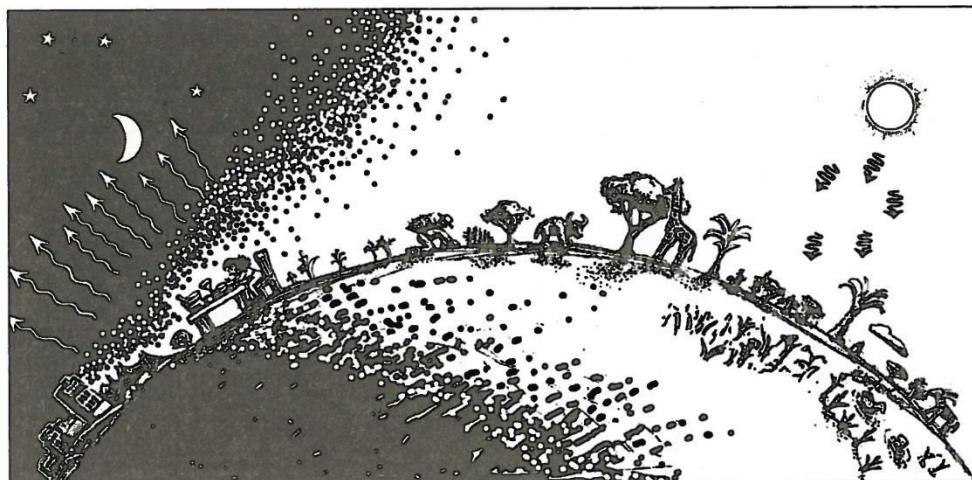


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# Epilogue: Life and Thermodynamics

## Example: Free energy from the Sun

- ✓ The Earth is exporting **much more** entropy than it receives: this is the entropy **generated** by the maintenance of all the **low entropy (ordered) structures** on the Earth...
- ✓ ...like hurricanes, the water cycle (raising water from the oceans high up into the clouds, falling as rain, etc.), temperature gradients due to the Sun (non-equilibrium), etc., and, of course, life itself

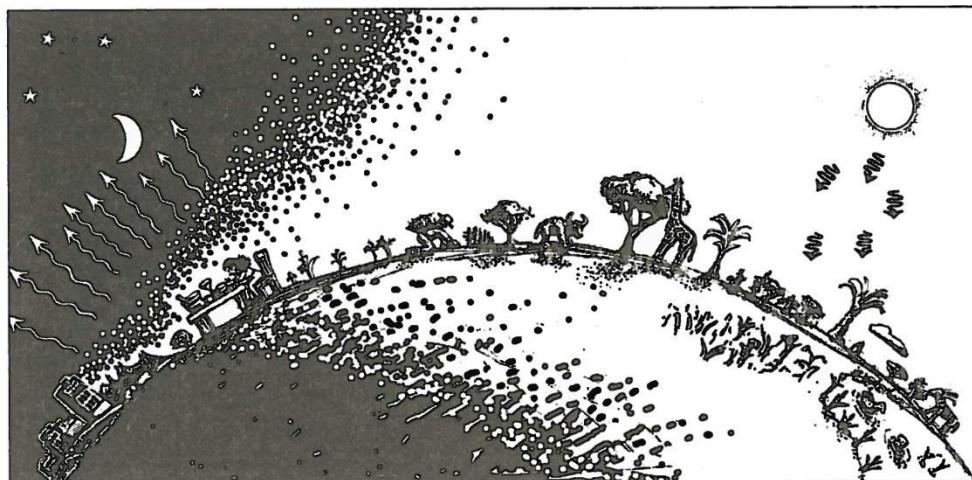


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# Epilogue: Life and Thermodynamics

## Example: Free energy from the Sun

- ✓ What's crucial in all this is that **the Sun is a hot spot in an otherwise cold sky**
- ✓ If the entire sky were as hot as the Sun, then its energy would be of no use to life on Earth. Ditto for the water cycle (which depends on a warm Earth and a cold sky), etc.
- ✓ So **why** is the Sun a hot spot in an otherwise cold sky?



Picture from Roger Penrose's  
*Cycles of Time: An Extraordinary  
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## Question 1: Why is the Sun a **hot spot**?

- ✓ The obvious answer is **thermonuclear fusion**.
- ✓ But the question we're **really** asking is:
  - How is it that the Sun is a source of **low-entropy energy**?
  - Equivalently, where does the Sun's **free energy** come from?
- ✓ In the next part of the course we will trace the source of the Sun's free energy back through ever lower and lower entropy states of the universe.
- ✓ We will see that the universe must have started (at the Big Bang) in a relatively **very low entropy state**. This is one of the most significant facts about our universe, but is still **deeply mysterious!**



## Question 2: Why is it an otherwise **cold sky**?

- ✓ This is equivalent to the question: **Why is it dark at night?**
- ✓ The obvious answer is: The Sun isn't shining!
- ✓ But it's more subtle than that... In the next part of the course we will see that the darkness of the night sky is intimately connected to the fact that our universe is not infinitely old, but of **finite age**—it had a **beginning**. This beginning is *also deeply mysterious!*
- ✓ The fact that life exists at all—the **origin of life**, is thus *intimately intertwined* with two of the greatest mysteries of all time: the **origin of the universe itself**, in such a **low entropy state**.



# Are We Alone?

But before that, we'll take a look at the question of extraterrestrial life...