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***.

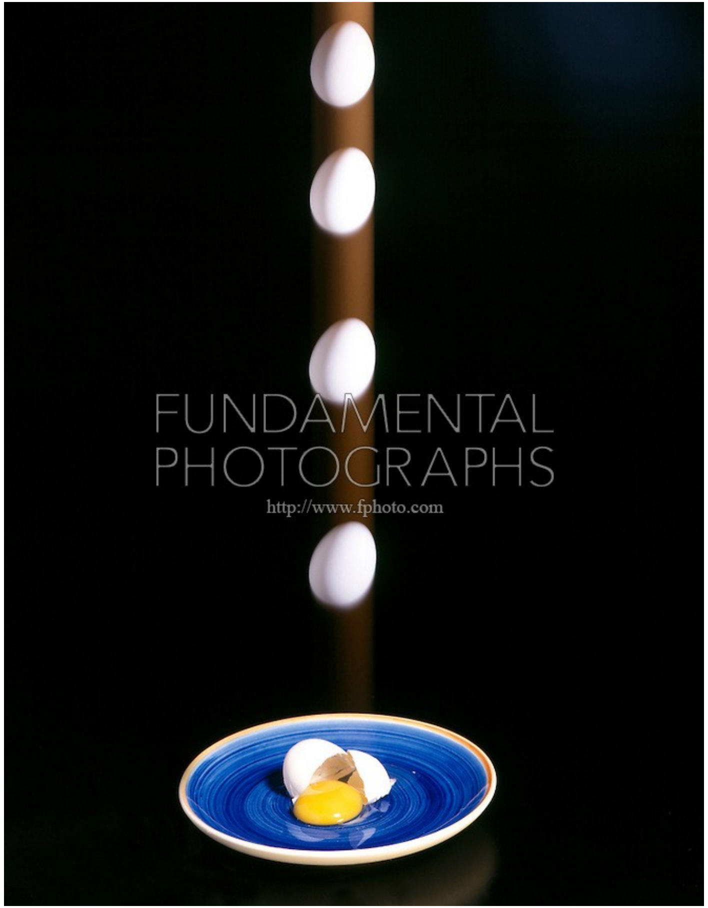
Introduction

- *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?**

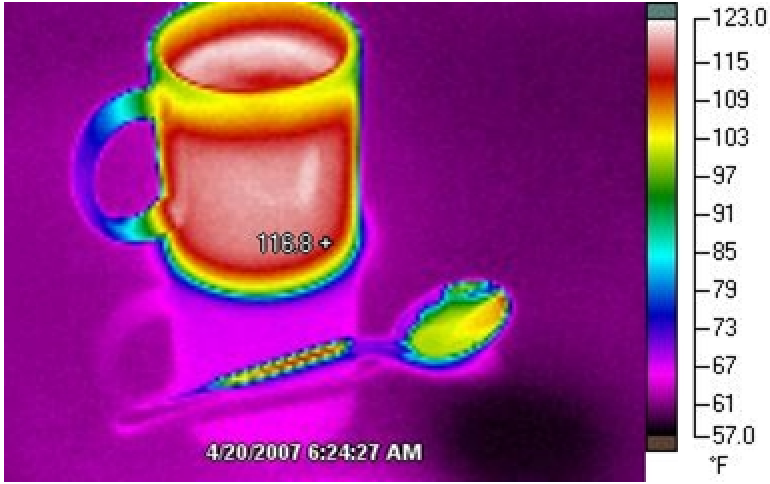
- What is the origin of this apparent **time asymmetry** in the way nature works?

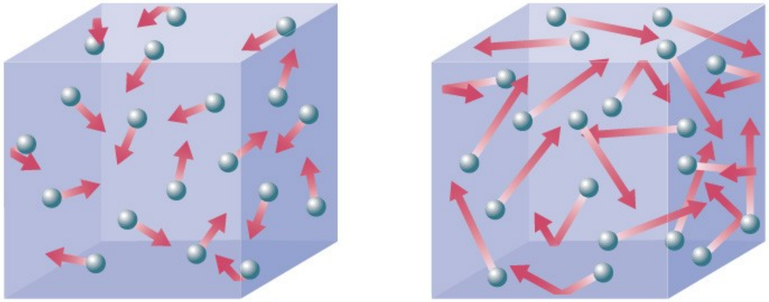


- **Simpler example:** When a hot cup of coffee cools to room temperature, thermal energy flows from the coffee molecules to the air molecules, in a way that **conserves total energy**.

- 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**?

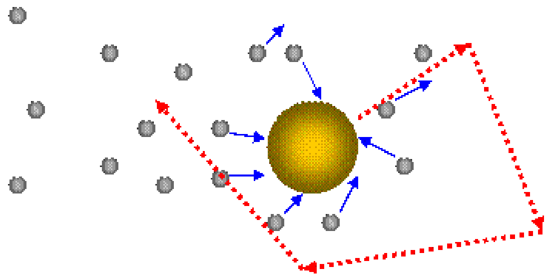
- There must be *another* law at work, beyond conservation of energy. This other law seems to involve the **direction of flow** of energy, or how energy tends to **distribute** itself.

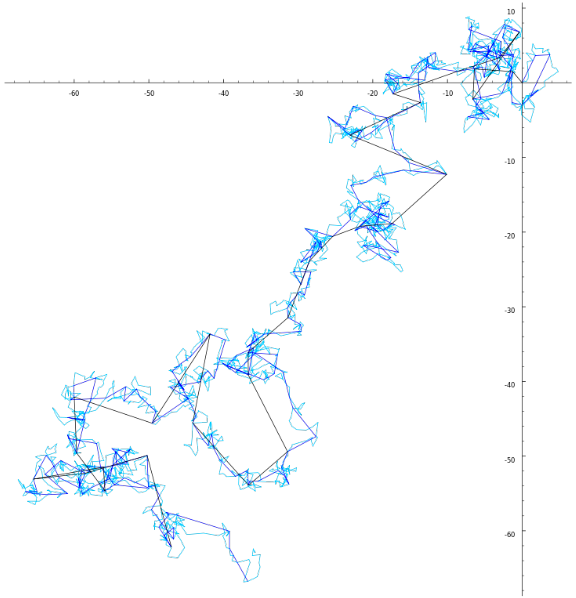




Longer arrows mean higher average speed.

- **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

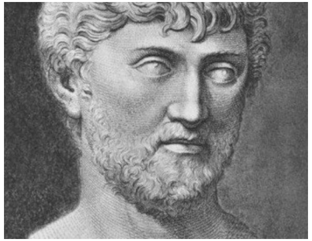
History:

- **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.

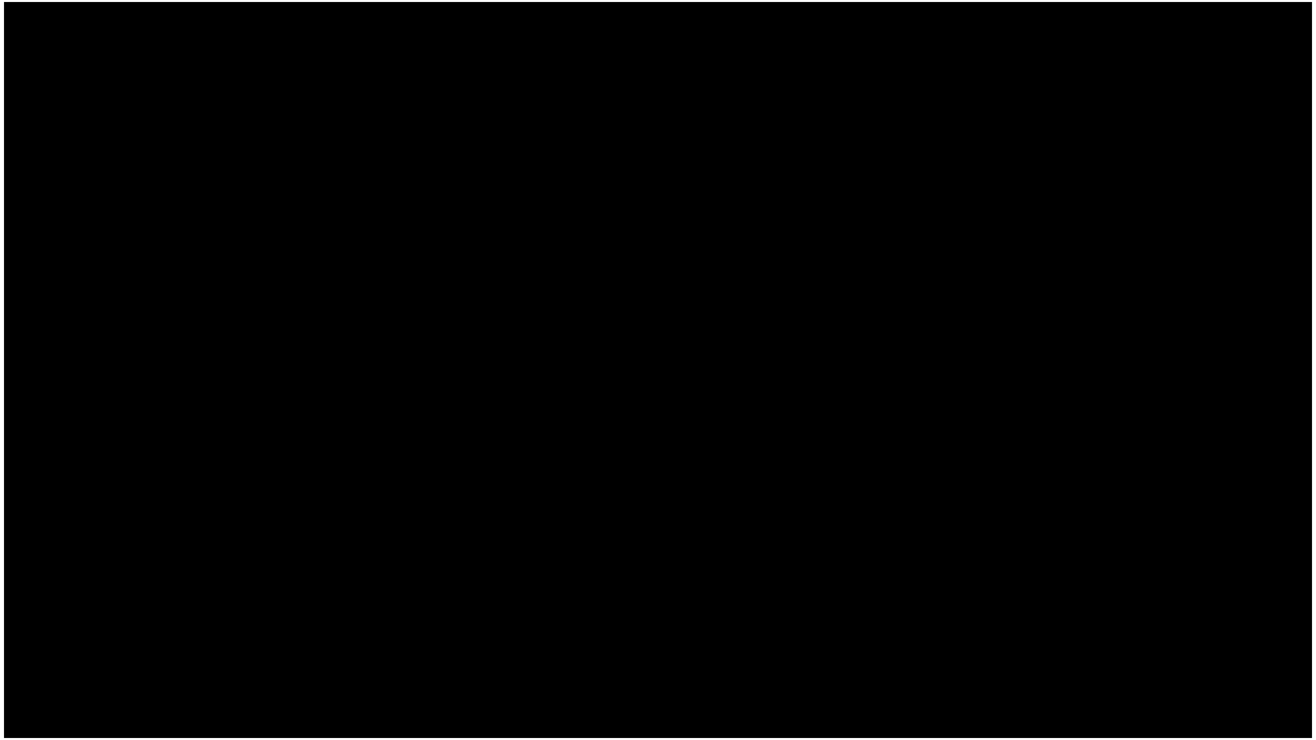
- Mathematical descriptions began in the late 1800s; **Einstein** (1905) made a detailed **quantitative** analysis of Brownian motion that provided definitive confirmation that atoms and molecules actually exist.

- **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.

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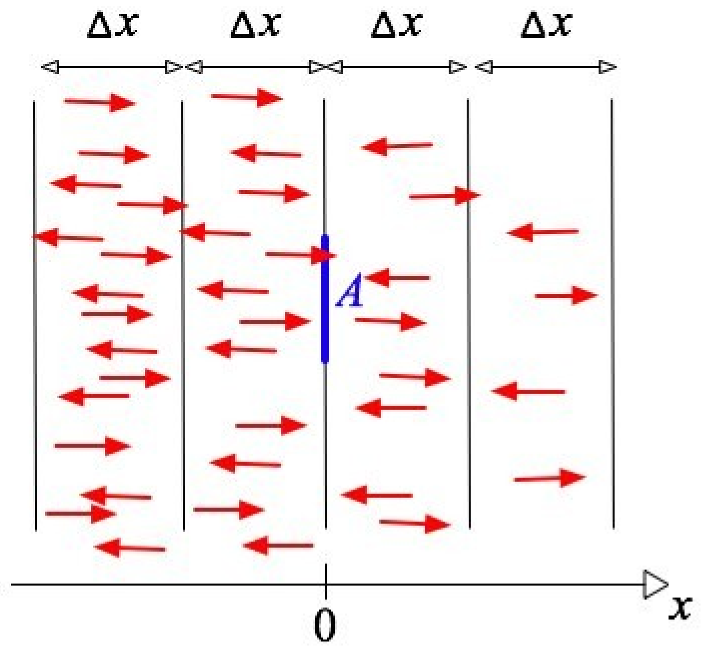
- Diffusion is similar to Brownian motion: Each particle moves **independently** of the others, in **purely random** thermal motion. *So why is there a **net migration** from higher to lower concentration?*

- **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).



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

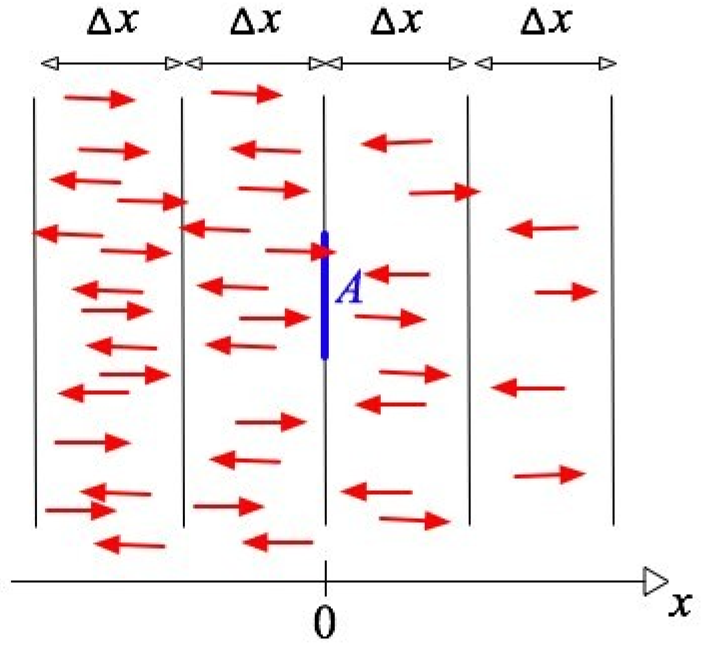
“Law from lawlessness”

“Law from lawlessness”

Diffusion

- Diffusion continues until there is an **equal** concentration of particles in all layers ⇒ **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.



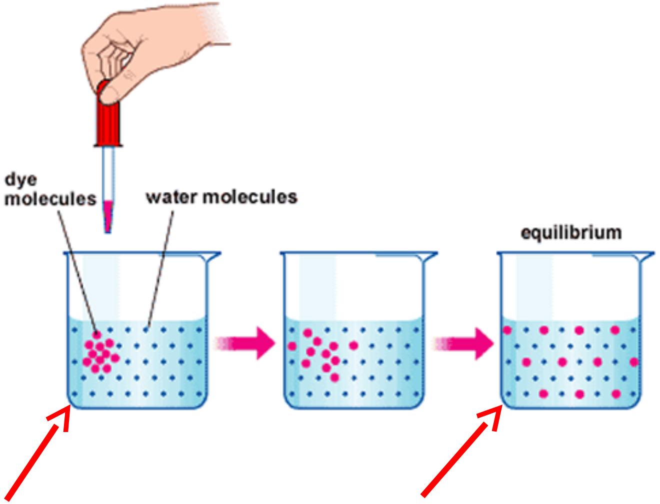
$$\frac{\partial \rho}{\partial t} = D \, \frac{\partial^2 \rho}{\partial x^2}$$

"Law from lawlessness"

"Law from lawlessness"

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 **stupend-ously** more uniform-like states than even the slightly less uniform-like states a moment before. The system inexorably **ratchets** towards equilibrium.



Few **micro**scopic states look like this **macro**scopically

Many **micro**scopic states look like this **macro**scopically

Diffusion

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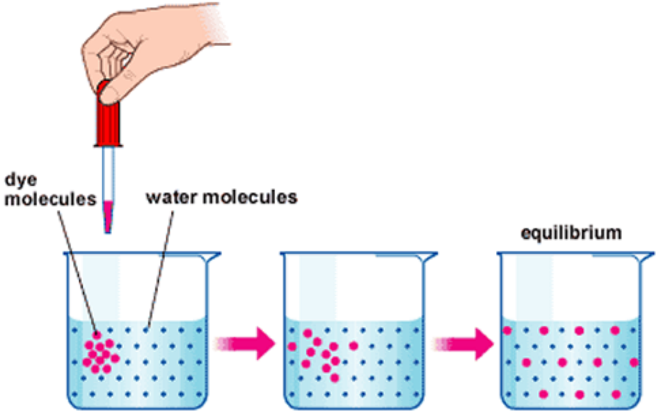


There's **no reason** system can't go back to the original state. It's merely **stupendously unlikely**.

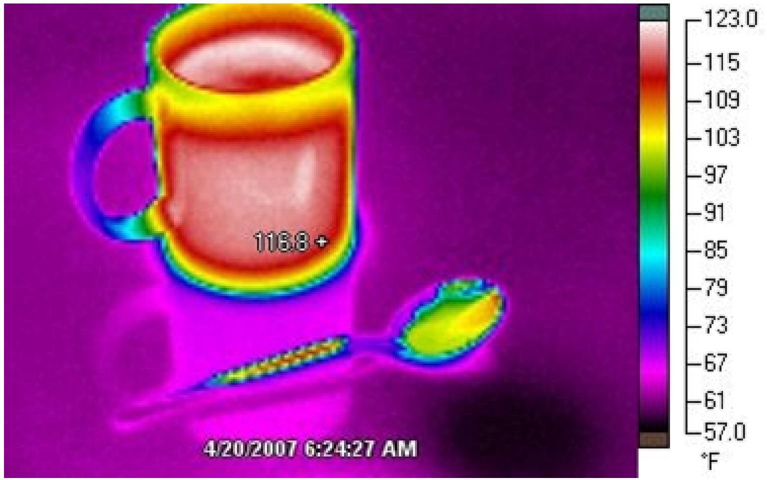
Process is **irreversible** just by the **"law of large numbers".**

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.

- 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 of Thermodynamics:** <u>The entropy of an isolated system never decreases</u>

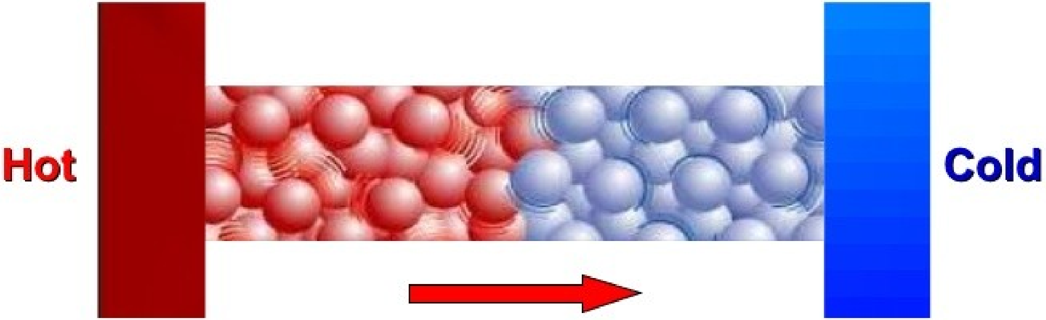
  This is perhaps the most potent statement in all of science, rivaled only by the first law of thermodynamics: the law of conservation of energy.

- 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.

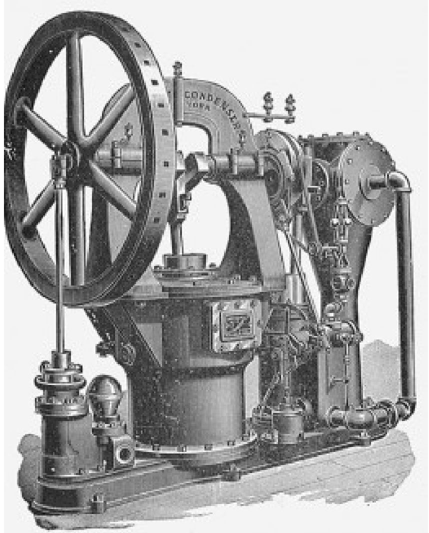
- While energy is **conserved** (and thus eternal), it is continually being **degraded** into a lower quality (more spread out) form. (Recall “heat death” of the universe.) While this might sound bleak, it is precisely this lawless, purposeless process that is responsible for virtually **all change** 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:



Q = amount of thermal energy transferred



$$\Delta S = S_f - S_i = \frac{Q}{T}$$

$\Delta S_{\text{hot}} = -Q/T_{\text{hot}} < 0$ (entropy of hot object **decreases**)

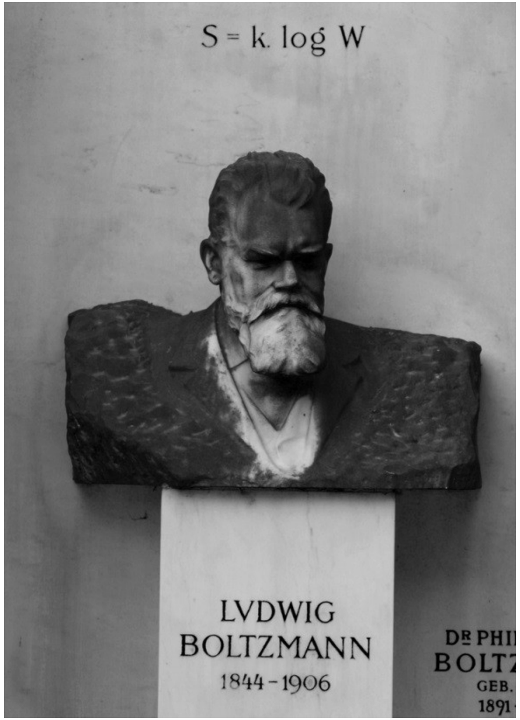
$\Delta S_{\text{cold}} = Q/T_{\text{cold}} > 0$ (entropy of cold object **increases**)

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 ⇒ **net increase**

Entropy

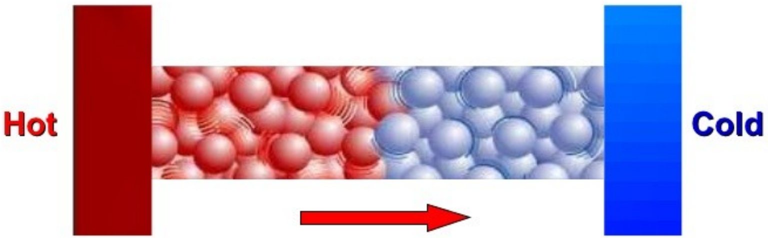
- **Entropy** was later understood much more deeply, at the *microscopic* level, by the great **Ludwig Boltzmann** (1844-1906), and summarized in his famous equation: $S = k\ \log W$

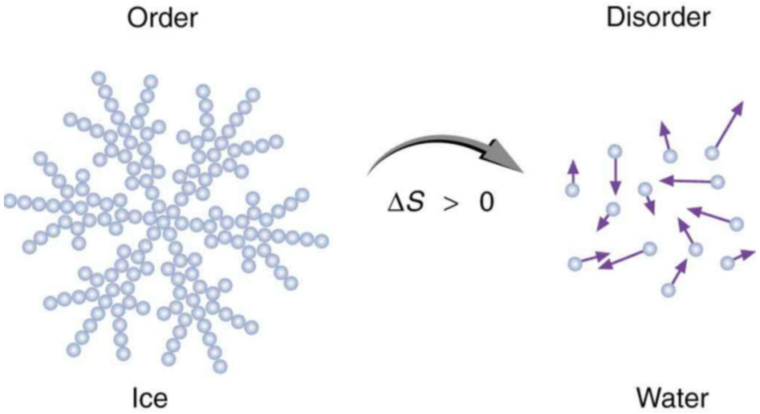


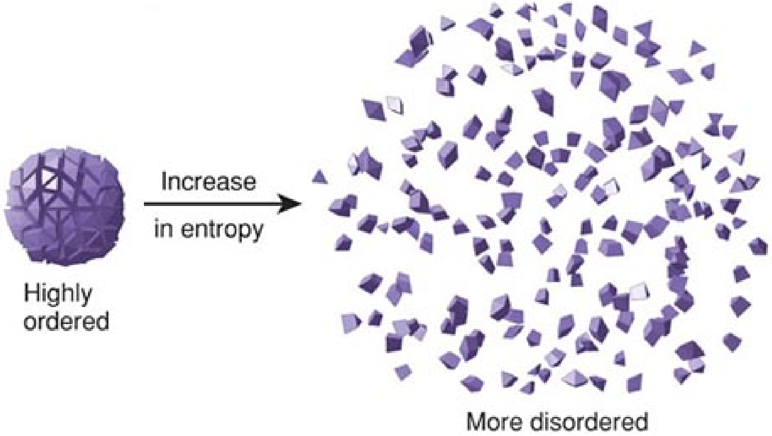
- $S = k \ \log W$

- 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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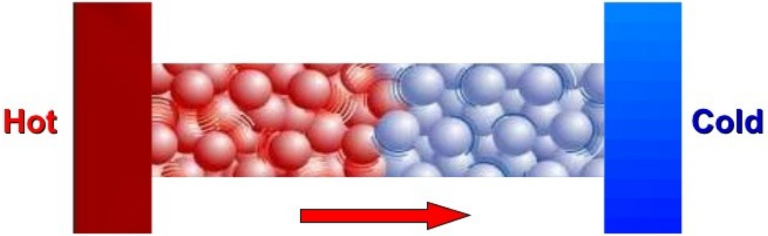
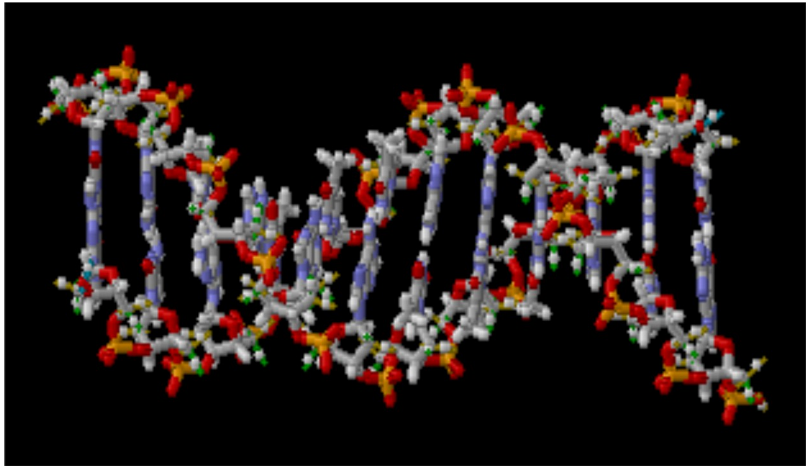


Periodic to "aperiodic" crystals: lower order/ complexity to higher order/complexity, or higher entropy to lower entropy



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

- $S = k \log W$ is used to **quantify** the amount of disorder, or entropy (S).

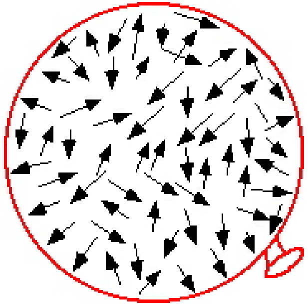
- k is called **Boltzmann's constant**, and has units of **energy per degree of temperature**. This tells us entropy is intimately connected with the concepts of **energy** and **temperature**, as we shall see. For simplicity we will set $k = 1$ (ignore this constant).

- $\log 100{,}000 = \log 10^5 = 5$. 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 = *number of* **microstates** *compatible with a given* **macrostate**.

Macrostates & Microstates

- The important quantity is W = *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 **micro**scopic states that would be *indistinguishable* (look the same to us) from a **macro**scopic point of view.



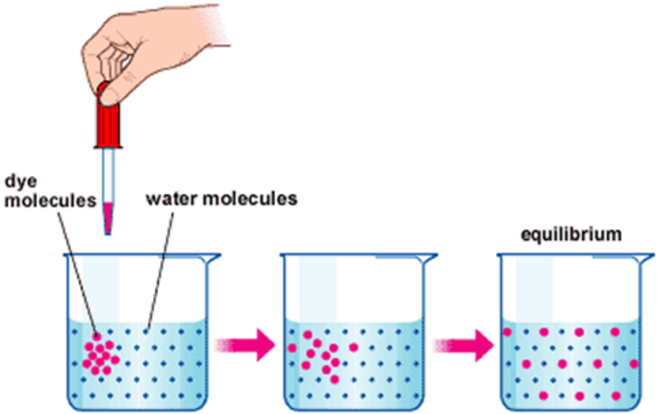
- The important quantity is W = *number of **microstates** compatible with a given **macrostate**.*

- 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 **micro**scopic states that *look the same* **macro**scopically, which we call W, increases very (**exponentially**) rapidly.



Few **micro**scopic states look like this **macro**scopically

Many **micro**scopic states look like this **macro**scopically

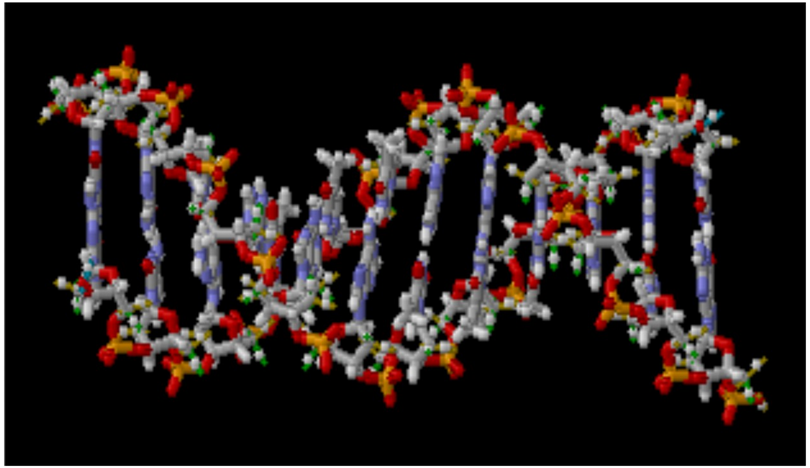
- "**Disorder**" is a vague word. The **precise meaning of entropy** is: $S = k \log W$.

- 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



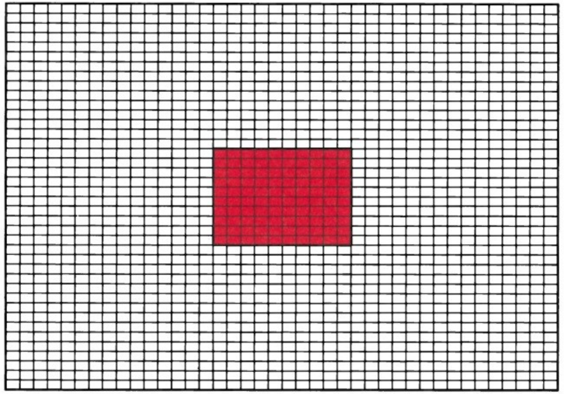
$S = k \log W$ is a powerful **bridge** between the **macro** and **micro** worlds.

is a powerful **bridge** between the **macro** and **micro** worlds.

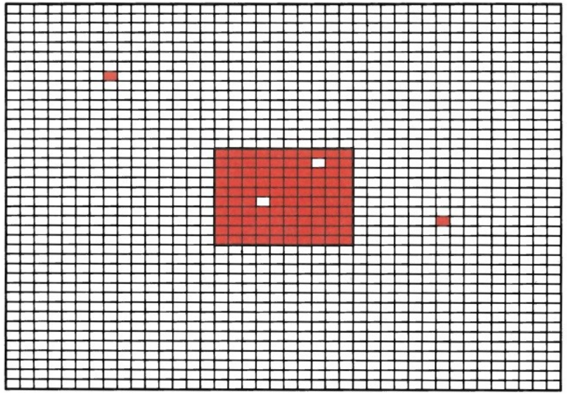
Example of $S = k \log W$ in action

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

- Universe = 40 x 40 = 1600 atoms
- System = 10 x 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")



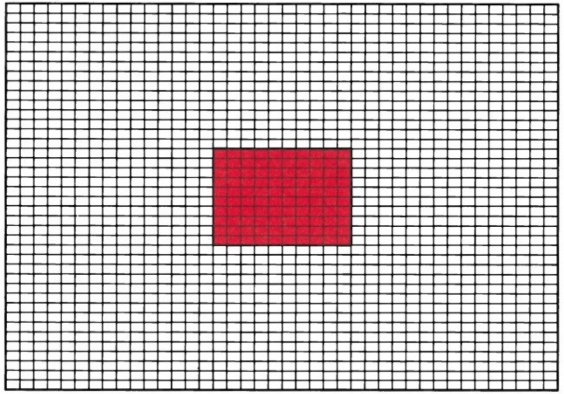
- Thermal motion of "ON" atoms jiggle neighboring atoms, transferring their energy: energy *naturally* disperses/diffuses

- But energy is **conserved**: **total** number of "ON" atoms = 100

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

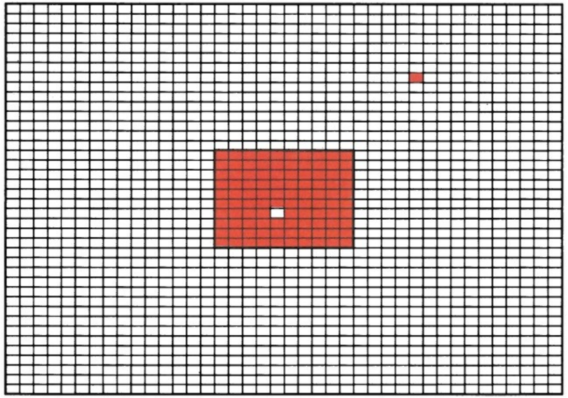
Initial entropy:

- 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:

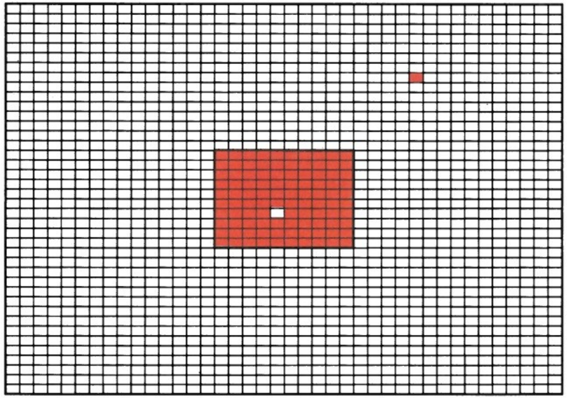


- **Temperature** is a measure of the **average** thermal energy per atom. Thus:
  - ✓ The temperature of the **system decreases**, and that of the **environment increases**, like the cooling cup of coffee warming the air in the room
  - ✓ The universe has taken the first step towards **thermodyna-mic 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

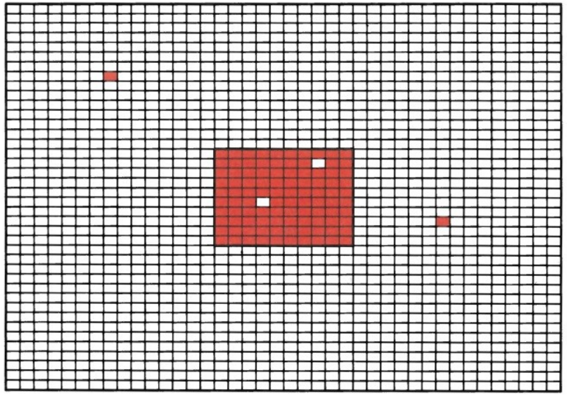
One unit of energy diffuses from the system into the environment:



- 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:



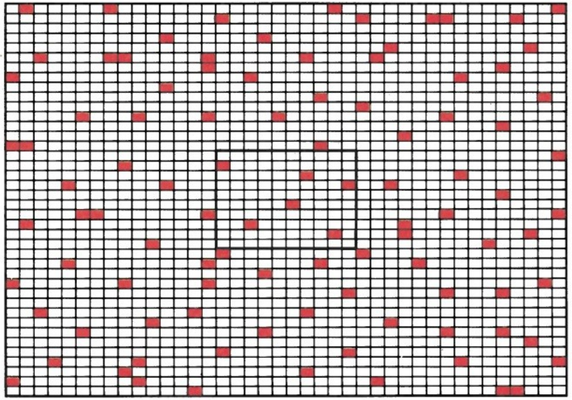
- The number of different ways **two “ONs”** can be distributed in the **environment** is $1500 \times 1499 \div 2 = 1{,}124{,}250$
- The number of different ways 98 “ONs” (or **two “OFFs”**) can be distributed in the **system** is $100 \times 99 \div 2 = 4950$
- The number of different ways **both** 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**

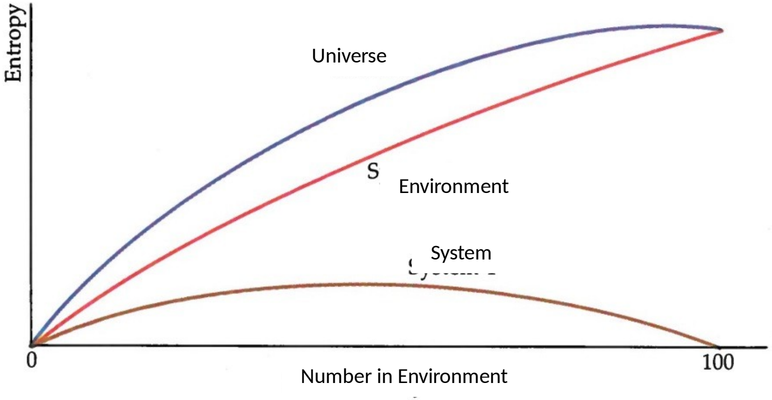
- In this example, **thermal equilibrium** corresponds to 6 or 7 “ONs” in the system, and 93 or 94 “ONs” in the environment, i.e., the **average** number of “ONs” is the **same** in both regions

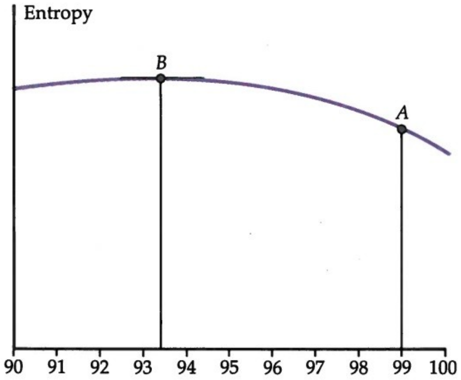


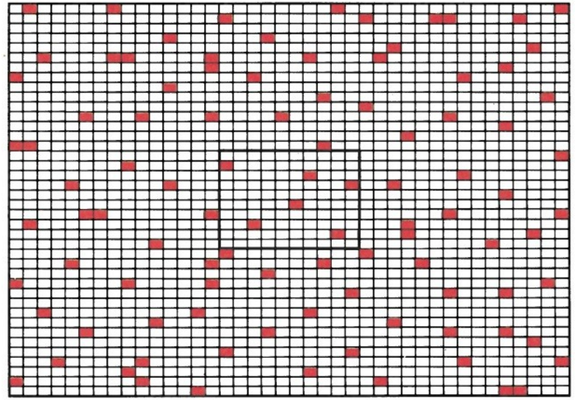
Example of $S = k \log W$ in action

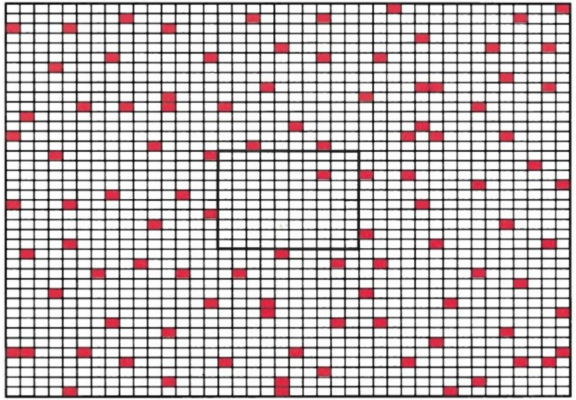
Example of in action

- **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**





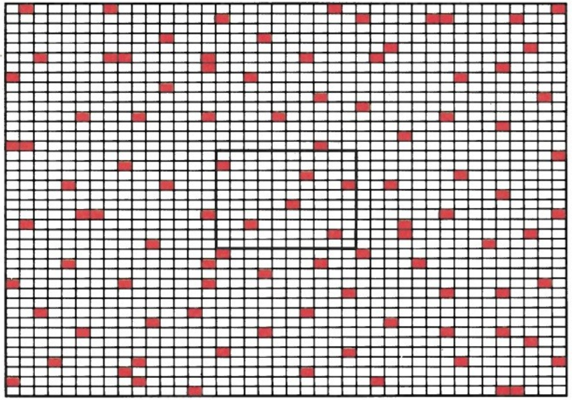


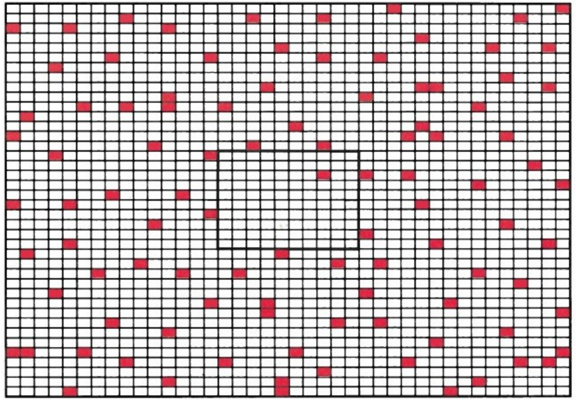


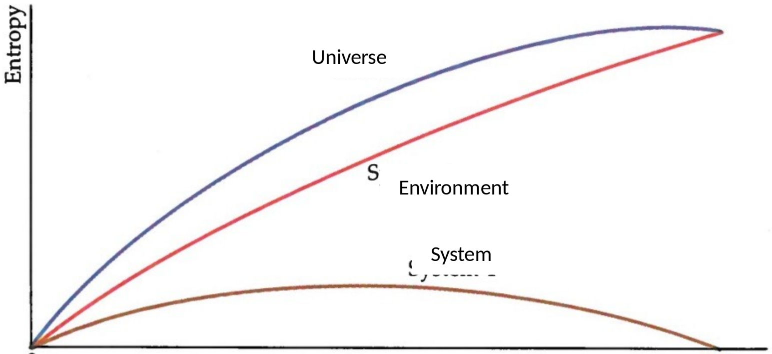
Example of $S = k \log W$ in action

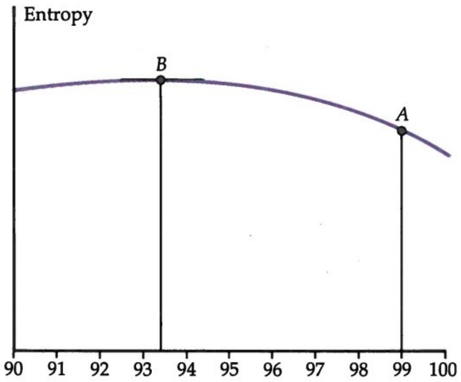
- **Thermal equilibrium** is also the point of **maximum entropy**

- 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



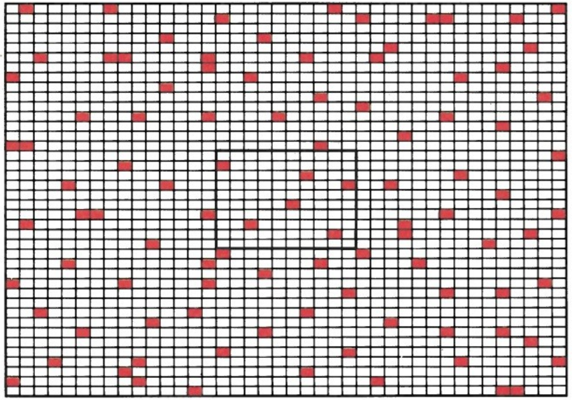


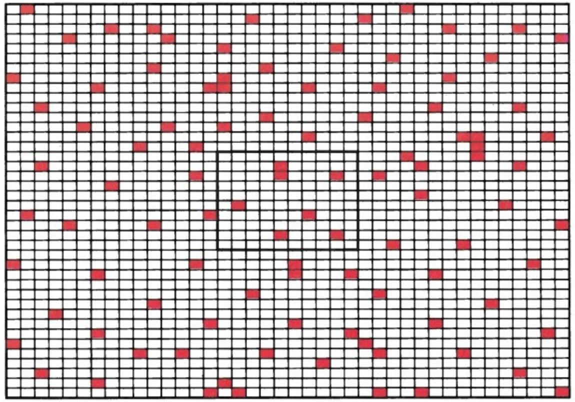


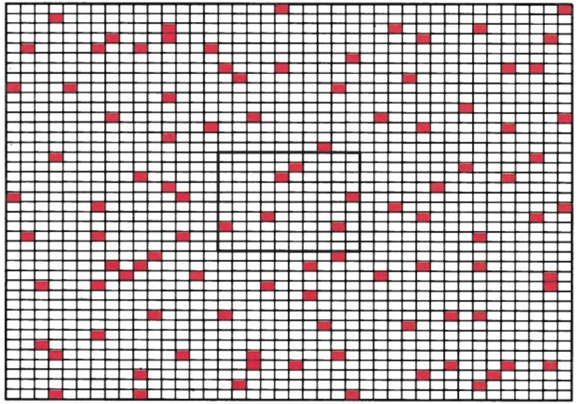


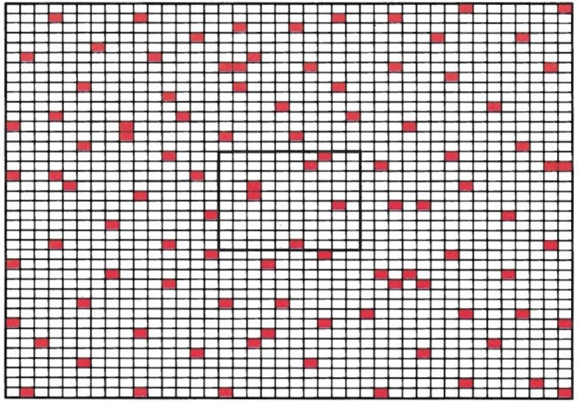
Example of $S = k \log W$ in action

- 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



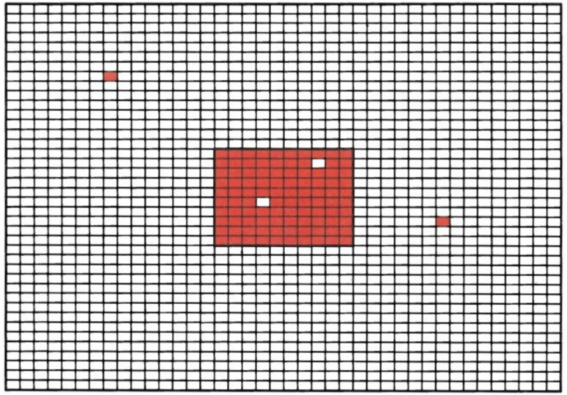


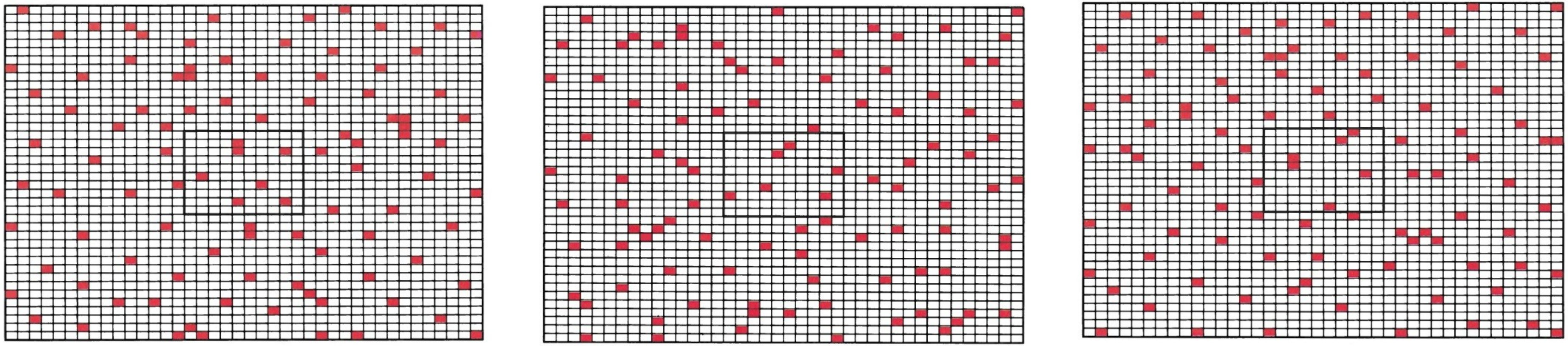




Example of $S = k \log W$ in action

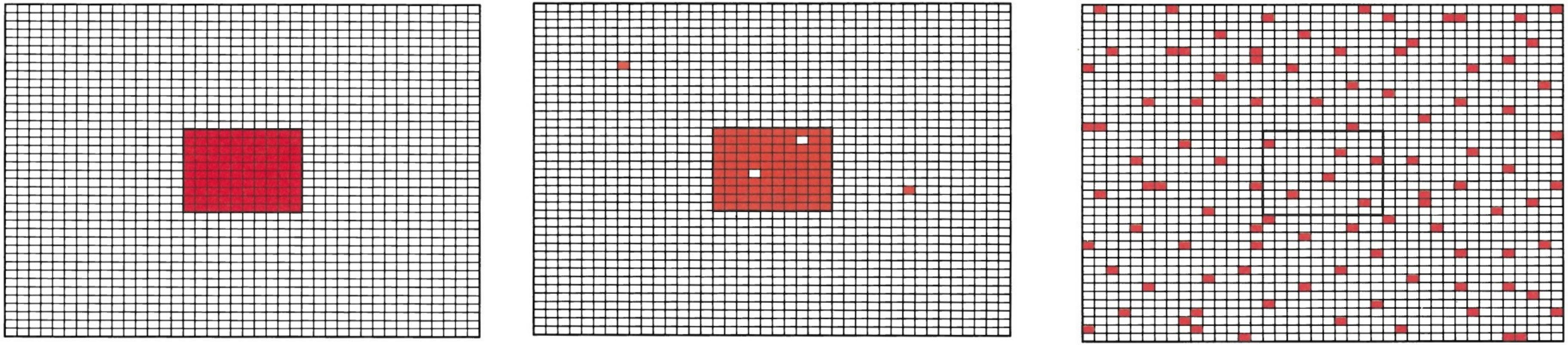
- Two additional points:
  - ✓ There are **stupendously** more microstates in the **thermal equilibrium** (**maximum entropy**) macrostate, compared to any other non-equilibrium macrostate. There's no reason the universe can't return to a non-equilibrium macrostate, it's just **stupendously unlikely**.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





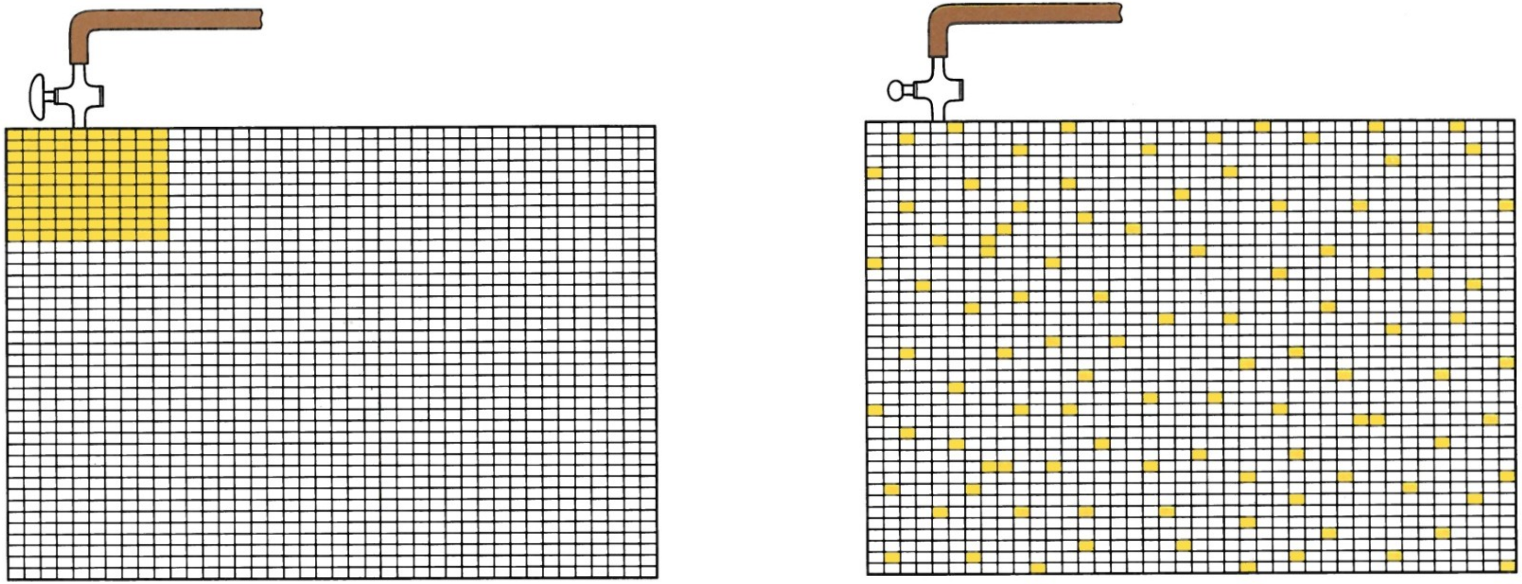
“Energy tends to disperse” ⇒ “Entropy tends to increase”

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



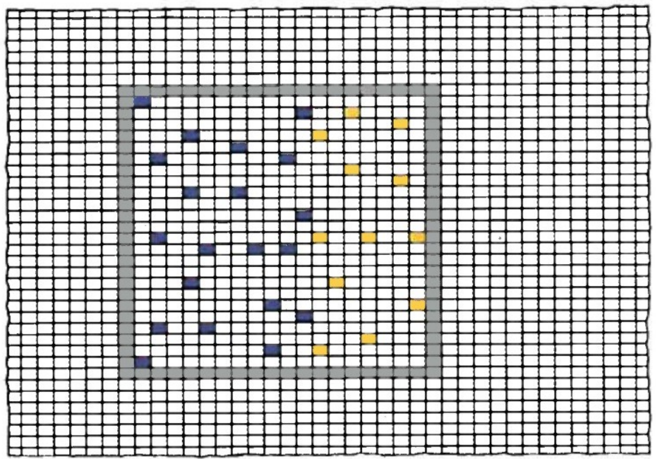
When **particles** disperse, entropy also increases.

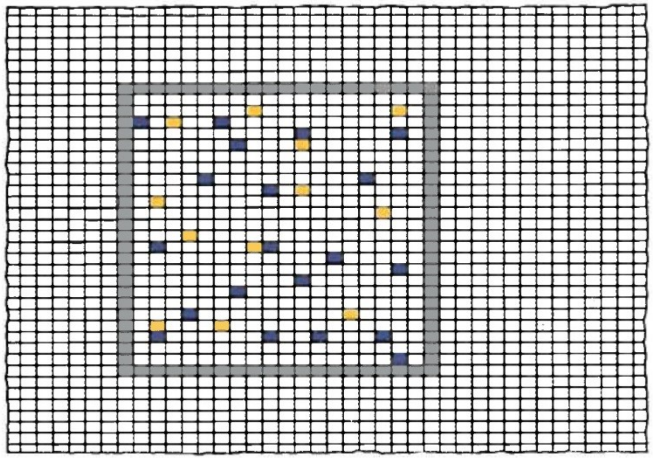
(There are **stupendously** more ways for particles to uniformly fill a volume, than to occupy one corner: $S = k \log W$ applies here too!)



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!)

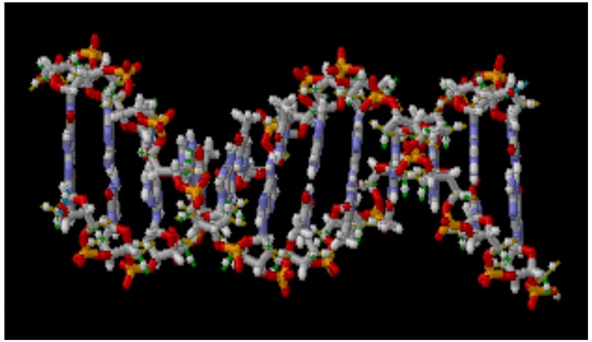


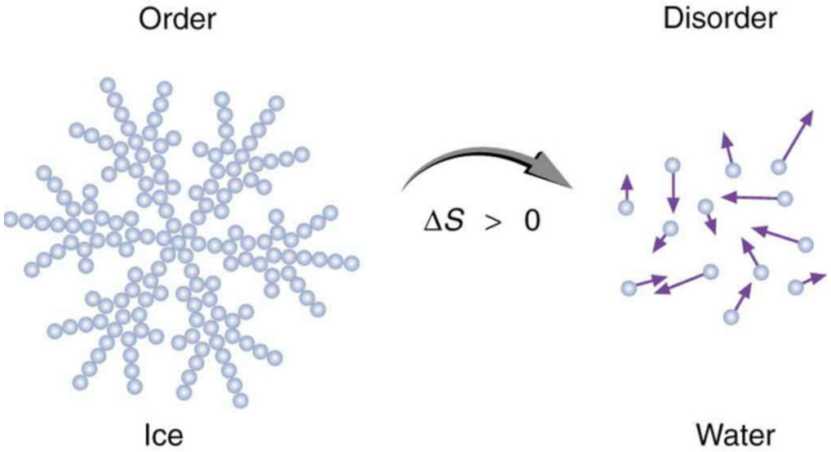


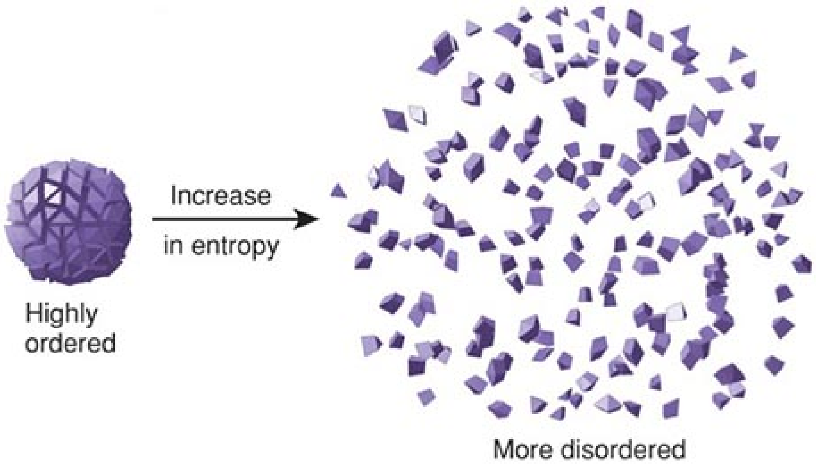
When **structural order** decreases, entropy **also increases**.

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!)







- 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.

Summary

So what?

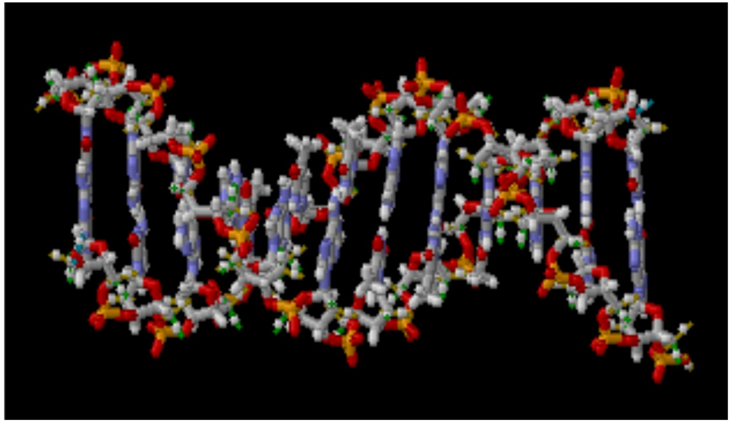
Life and the Second Law

- 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!?

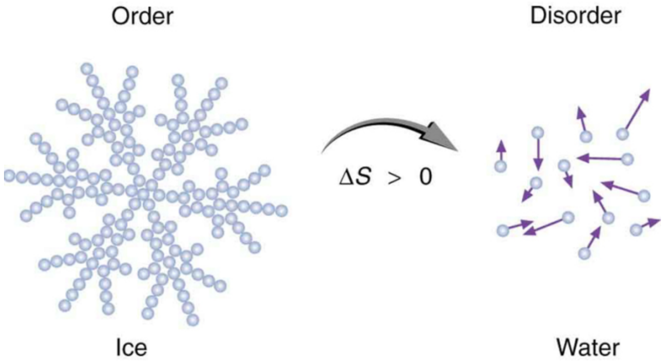
- **No:** The universal ratcheting towards disorder is only **on balance**. Entropy can **decrease** in one location, as long as it **increases more** somewhere else, such that the **total** entropy increases (or stays the same).



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_2O**.
- The water-to-ice transition **releases** energy (“latent heat”) because H_2O bonds in ice are more stable (**stronger/lower energy**) than H_2O 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 ⇒ ***net* entropy increase**.
- A freezer **does not** violate the Second Law.



Life and the Second Law

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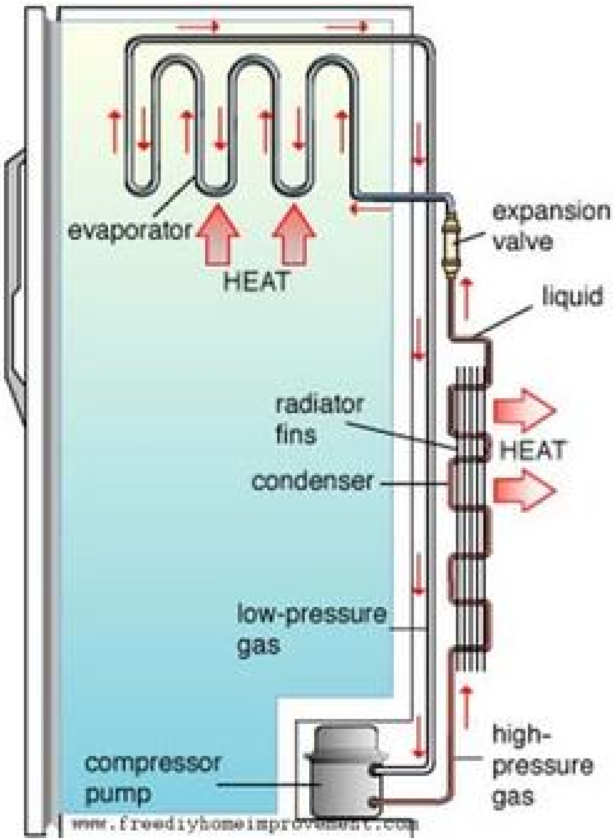
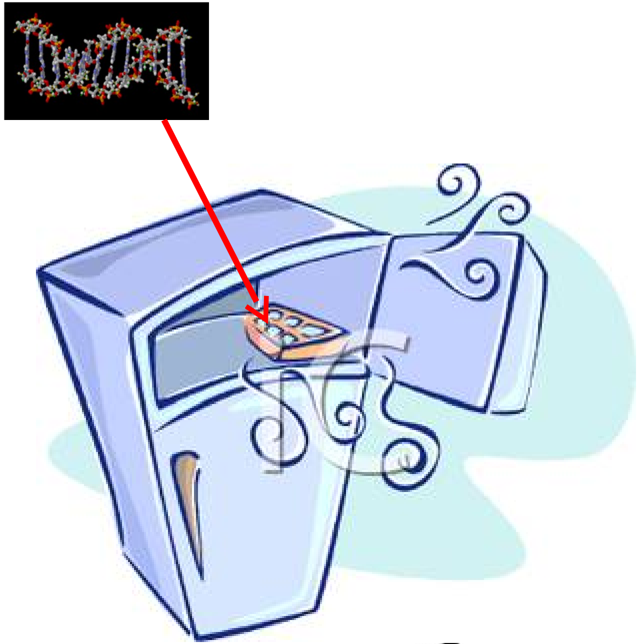


Life and the Second Law



- 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:

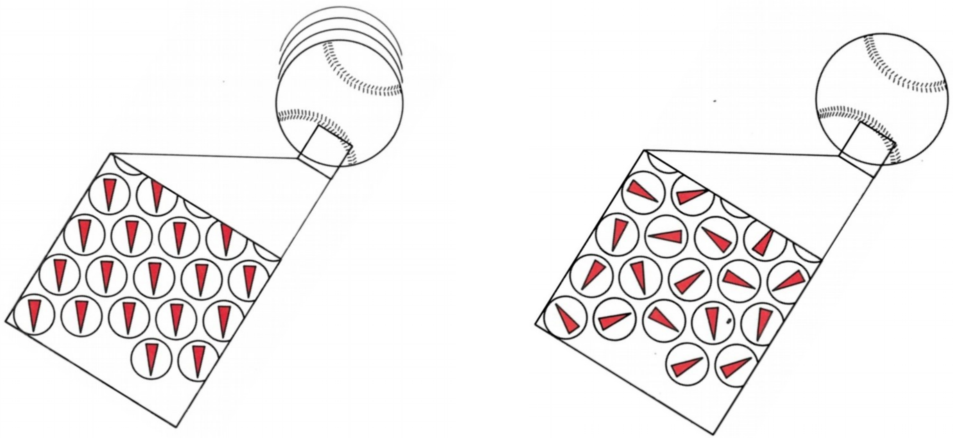
  - ✓ …but now in much more detail, to see how it actually works

  - ✓ …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

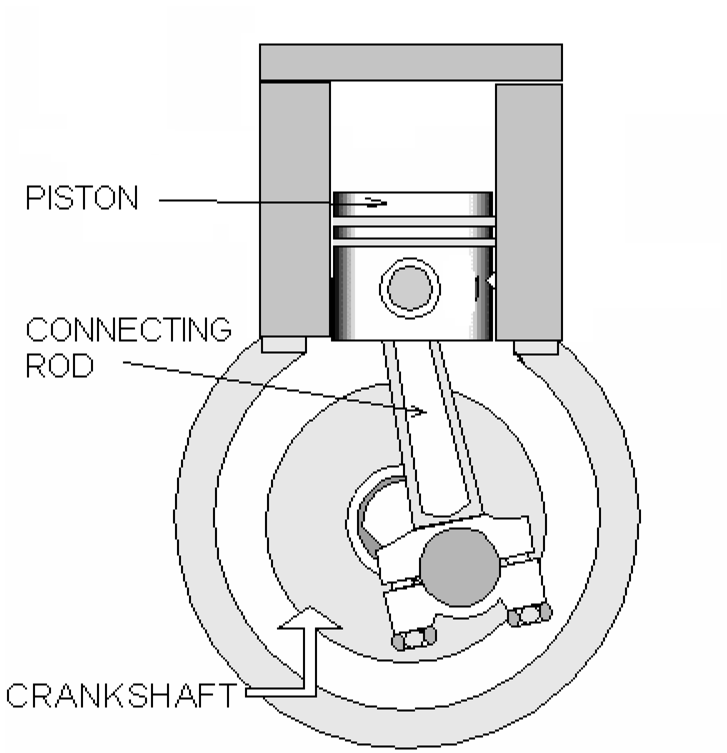
  - ✓ …this is a central theme to understanding what life is

- 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!

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



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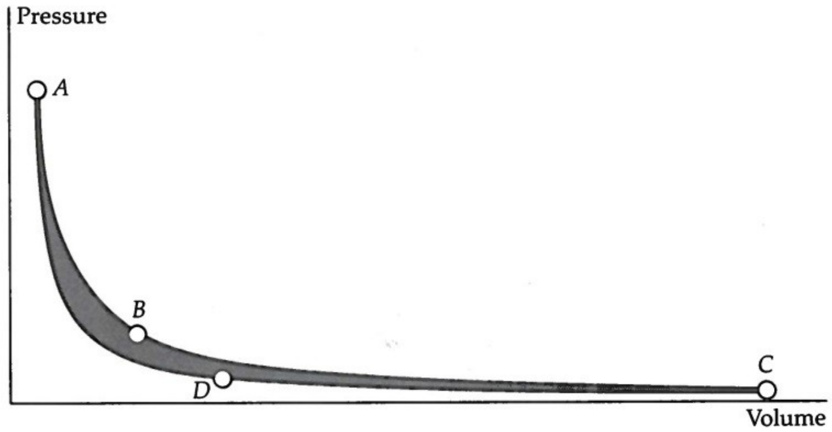
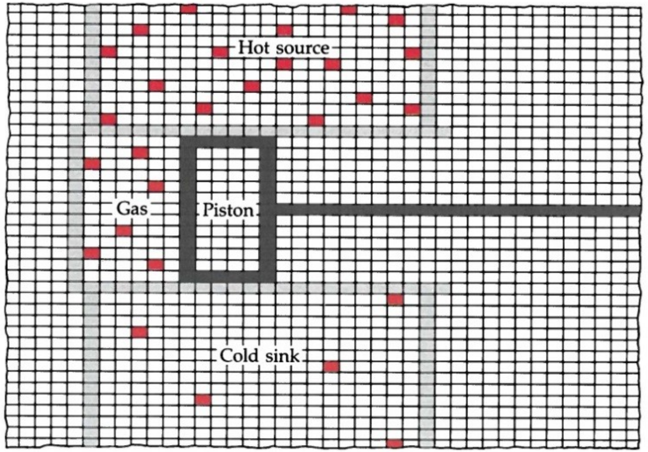
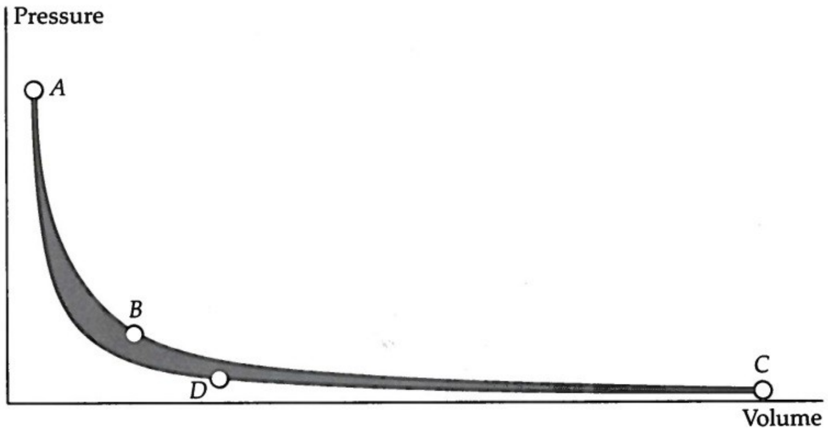


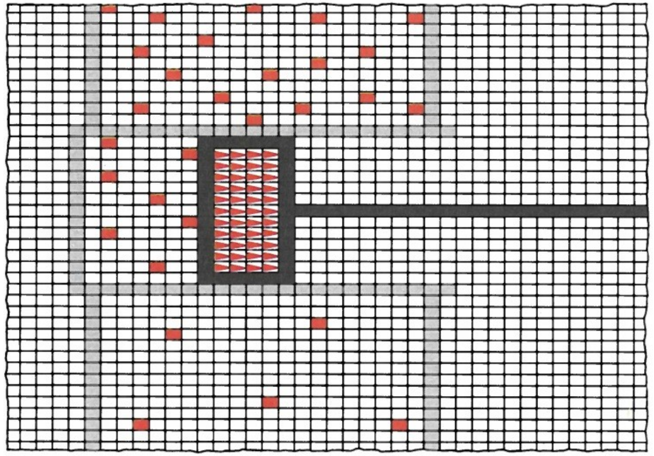


- Above is a simpler version of a car engine that works on what’s called “Carnot cycle”
- A fixed amount of gas is contained in a cylinder with a moveable piston
- The gas can be alternately brought into contact with the “hot source” or the “cold sink”

Order from Disorder

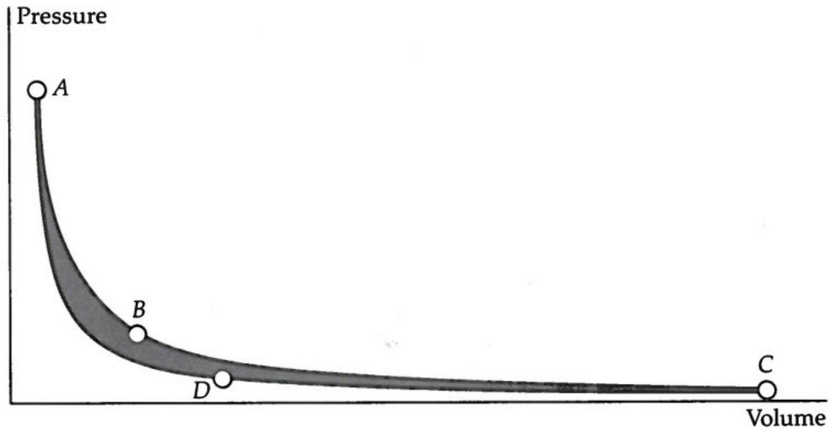
- Nevertheless, machines exist all around us that **spontaneously** create **order** from **disorder**

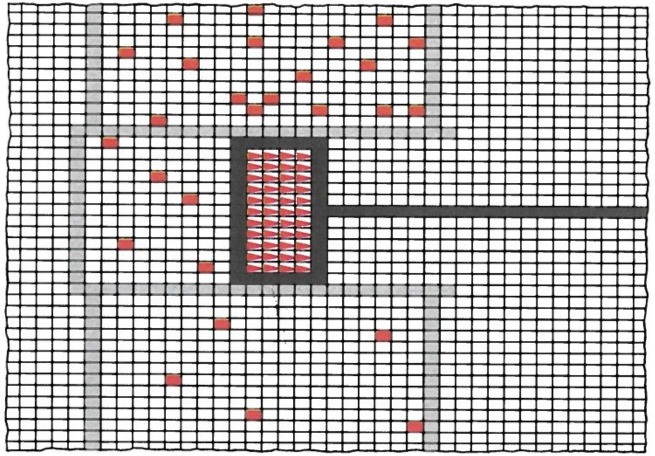




- **A-B:** The gas is in contact with the "hot source", and remains at the same temperature
- Hot gas atoms bombard the piston, which absorbs ***only right-moving KE (this is the key)***. **Disordered KE is converted into ordered KE!** As the atoms turn "OFF", fresh disordered KE *spontaneously* flows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

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

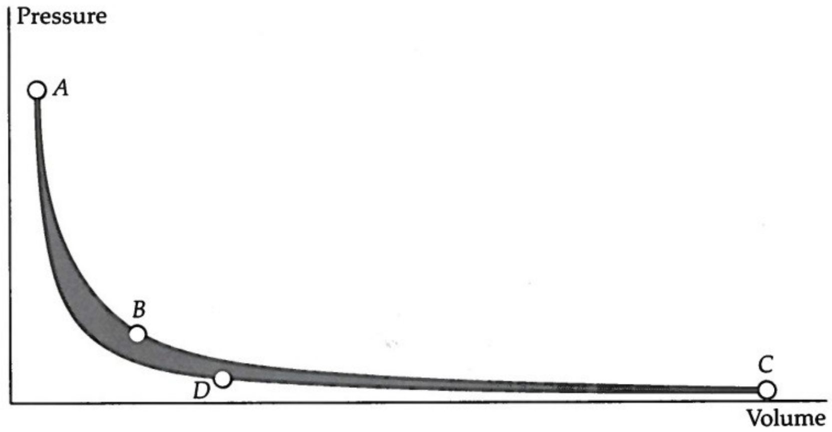


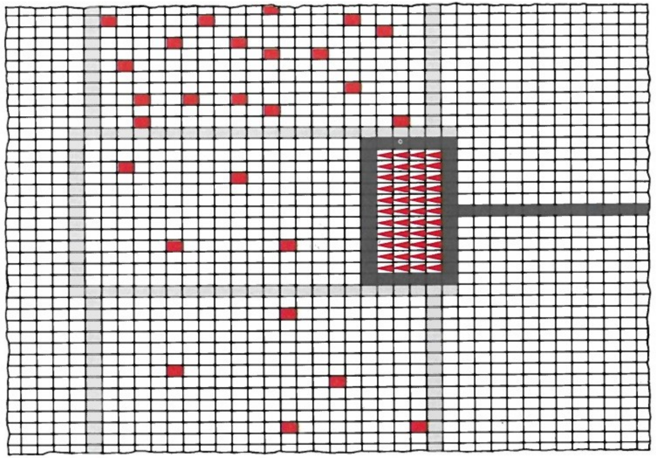


- **B-C:** The gas is isolated from the "hot source", and cools as it continues to expand
- Hot gas atoms continue to bombard the piston, but as their disordered KE is converted into the piston's ordered KE (gas atoms turn "OFF"), no fresh KE flows in from the "hot source", causing the gas to cool as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

Order from Disorder

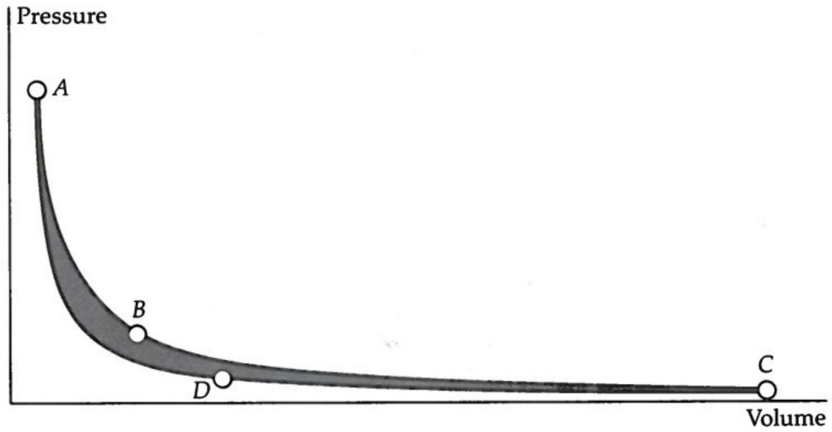
- Nevertheless, machines exist all around us that **spontaneously** create **order** from **disorder**

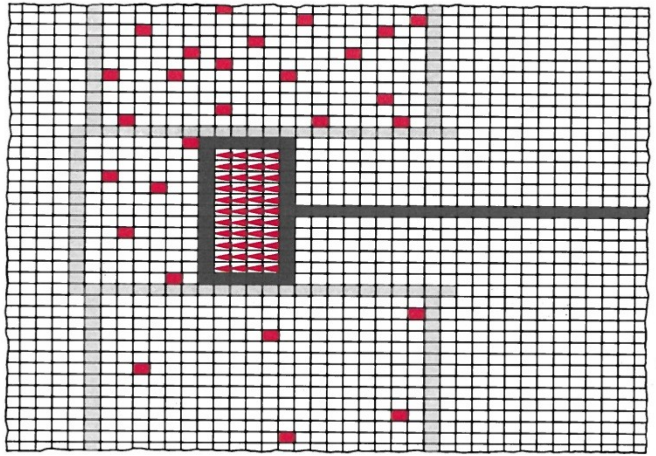




- **C-D:** The gas is put in contact with the “cold sink”, and remains at the same temperature
- The piston turns around and is now moving left, hitting the cold gas atoms, transferring to them ordered KE, which is quickly randomized by collisions into disordered KE. This would normally heat up the gas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

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



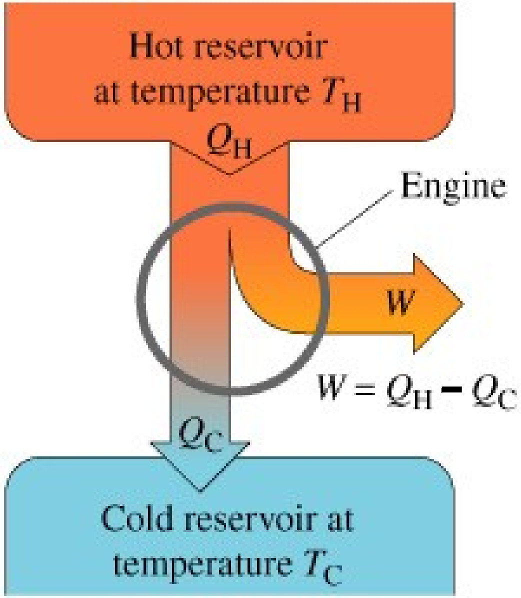


- **D-A:** The gas is isolated from the “cold sink”, and heats up as it is compressed
- The piston continues moving left, hitting the now warmer gas atoms, transferring to them additional ordered KE, which is quickly randomized by collisions into disordered KE. Because the extra thermal energy is not 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

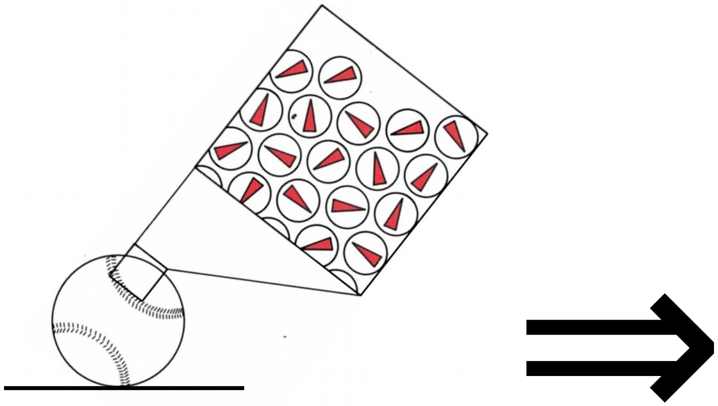
- Nevertheless, machines exist all around us that **spontaneously** create **order** from **disorder**

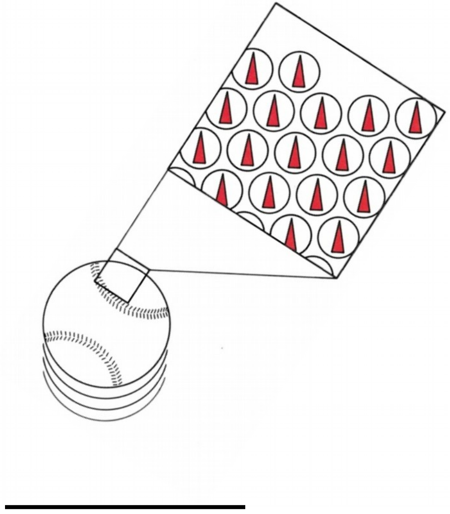
- Over one complete cycle:
  - ✓ **Disordered** KE (**thermal** energy) **spontaneously** flows **from the hot source into the gas in the** cylinder (Q_H) and from this gas into the cold sink (Q_C)
  - ✓ In the process, **ordered** KE in the form of the motion of the piston was extracted to do useful "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

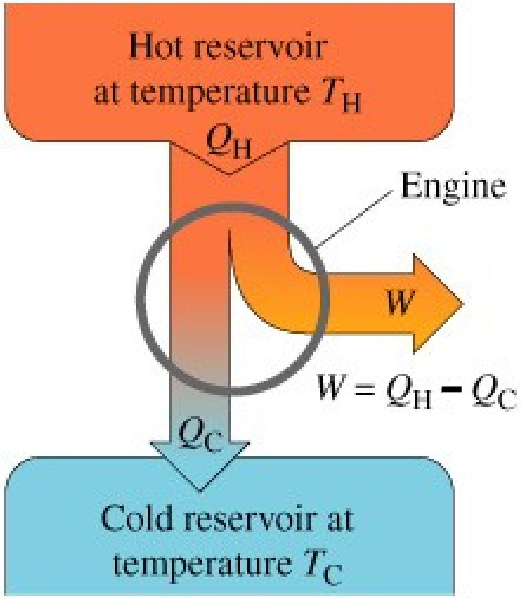
- Nevertheless, machines exist all around us that **spontaneously** create **order** from **disorder**

- Thinking in terms of **entropy**:

  ✓ In an **ideal** engine, $\Delta S = 0$:

  - $\Delta S_{\mathrm{H}} = -Q_{\mathrm{H}}/T_{\mathrm{H}} < 0$ (entropy of hot source decreases)
  - $\Delta S_{\mathrm{C}} = Q_{\mathrm{C}}/T_{\mathrm{C}} > 0$ (entropy of cold sink increases)
  - Ratios of temperatures and energy flows are such that: $\Delta S = \Delta S_{\mathrm{H}} + \Delta S_{\mathrm{C}} = 0$, just consistent with 2nd 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



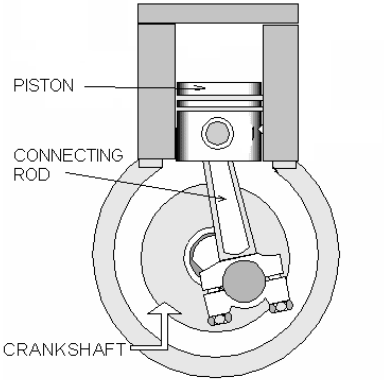
Order from Disorder

- 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?

- 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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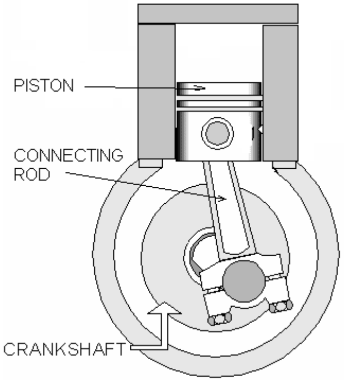
Order from Disorder

- 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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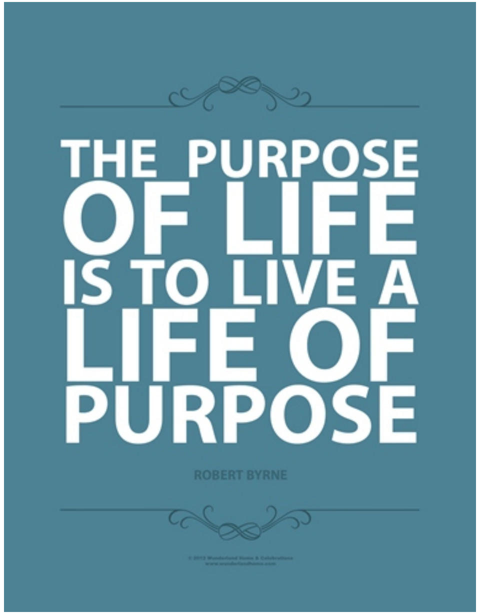
Order from Disorder

- 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”?



Order from Disorder

- ✓ 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!