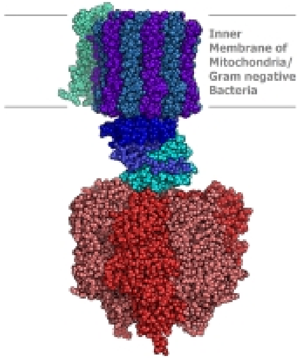
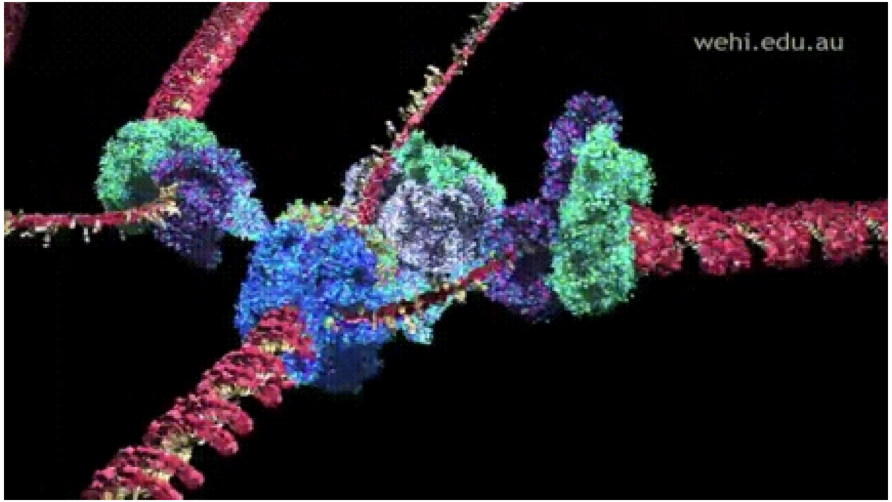
The Real Question

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

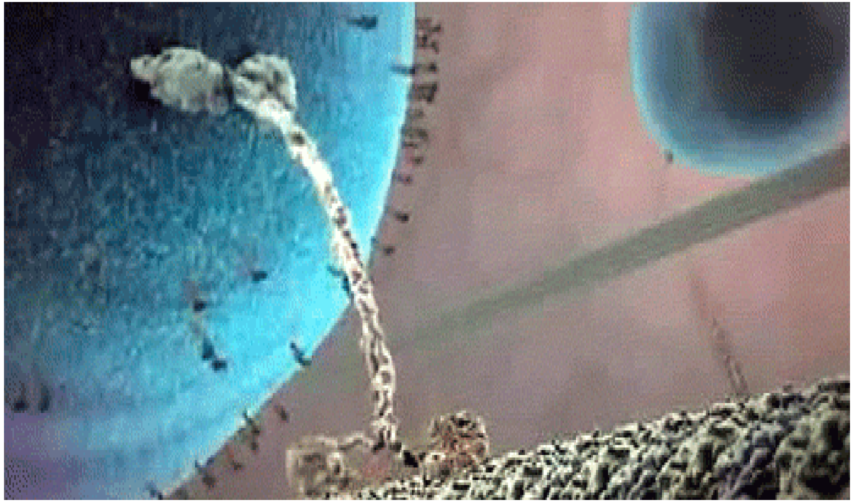


So the **REAL QUESTION** is:

How might such complex machinery have arisen ***<u>spontaneously</u>***?

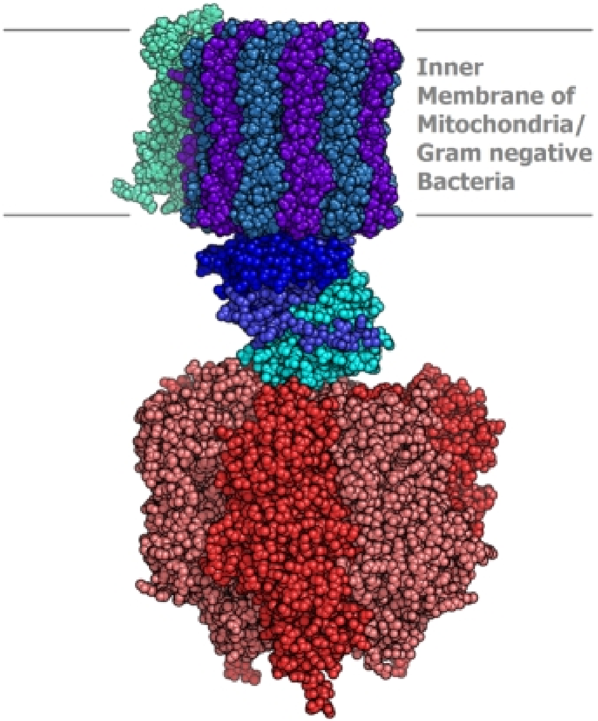


kinesin protein



Recall:

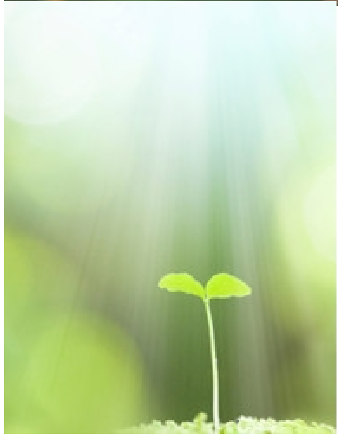
- Physicists have discovered two fundamental laws of nature:
  - ✓ 1st Law: **Quantity** of energy is **constant**
  - ✓ 2nd Law: **Quality** of energy **continually decreases**
- We have shown that life is **consistent** with these basic thermodynamic laws.
- But can thermodynamics explain **why** life 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!



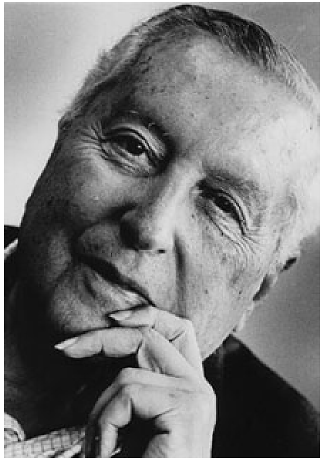
The Real Question

The problem is:

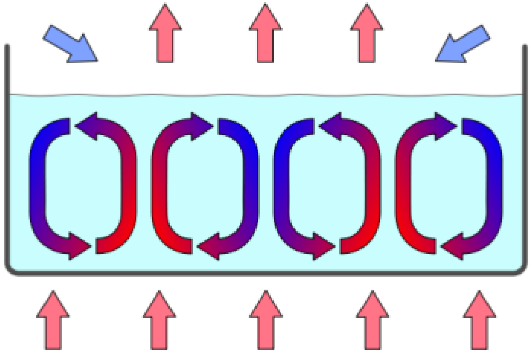
- Thermodynamics was originally the study of **closed systems** at or near **equilibrium**.
- But living organisms are:
  - ✓ **NOT closed systems:** They *exchange* matter and energy with their environment
  - ✓ **NOT in equilibrium:** They are continually *changing*, animated, not static
- Lane: "Cells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

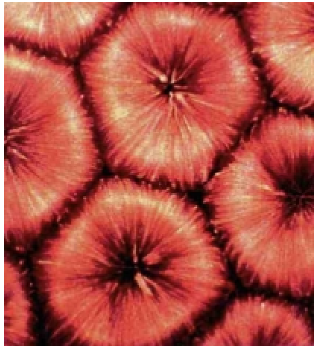


Dissipative Structures



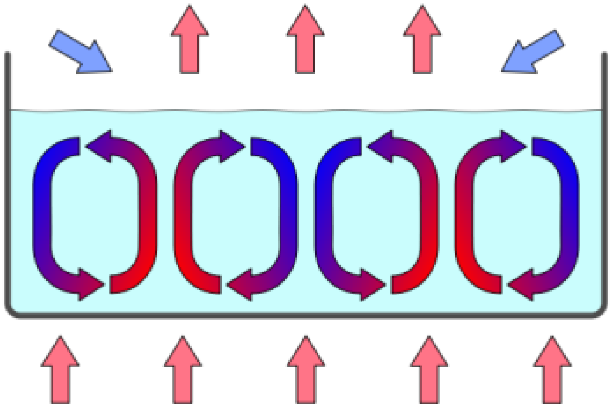
- Late 1960s–early 1970s: **Ilya Prigogine** (1977 Nobel Prize) discovered **dissipative structures** in systems that are:
  - ✓ **Open**: they have energy (or matter) **flowing through them**
  - ✓ **Non-equilibrium**: *Steady* state, but *not static* (flow = motion)
- Example: **boiling water** (or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



- This is *analogous* to a living organism:

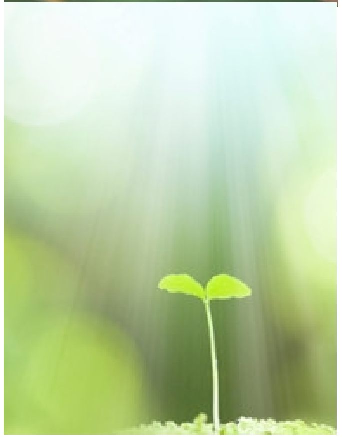
  - ✓ An **open** system with energy/matter **flowing** through it (sunlight, food, etc.), operating **out of thermodynamic equilibrium**

  - ✓ E_{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)

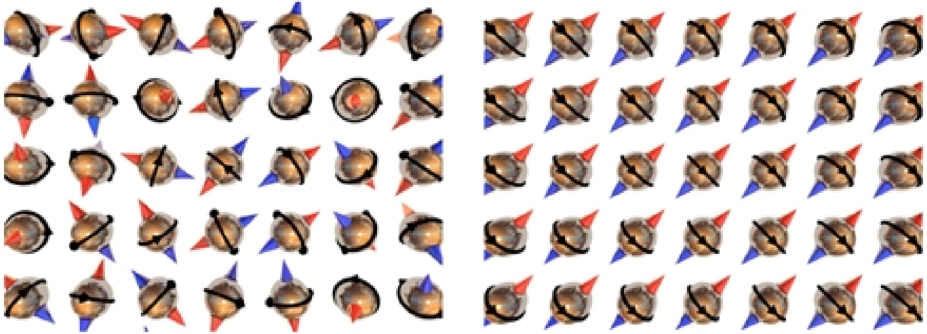
  - ✓ The system survives only while energy is being **dissipated** (dispersed, degraded). When it **stops**, the organism (ordered structure) **dies**.

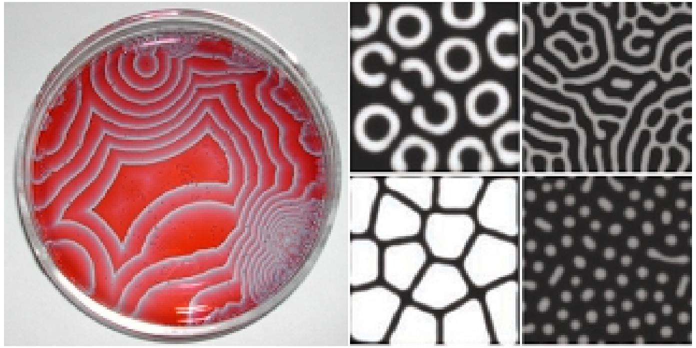
- ...*analogous*, yes, but life is a **much richer** phenomenon. **But it's a start!**



- **Dissipative structures** are related to **self-organizing** systems: order arises out of the local interactions between smaller component parts of an initially disordered system.

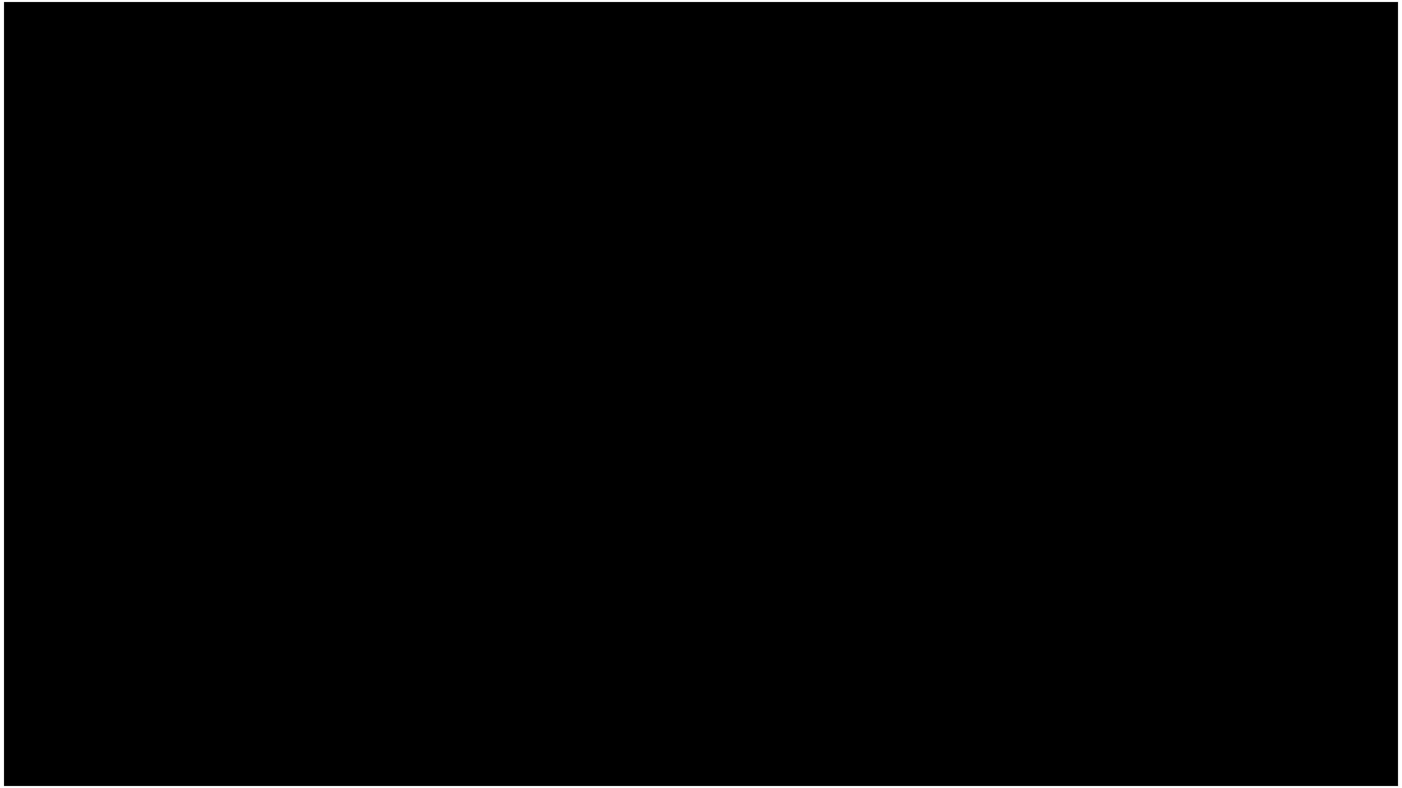
- **Many** examples of this general phenomenon:
  - Physics: Spontaneous magnetization
  - Chemistry: Oscillating & reaction-diffusion reactions
  - Biology: Birds flocking, fish schooling, etc.



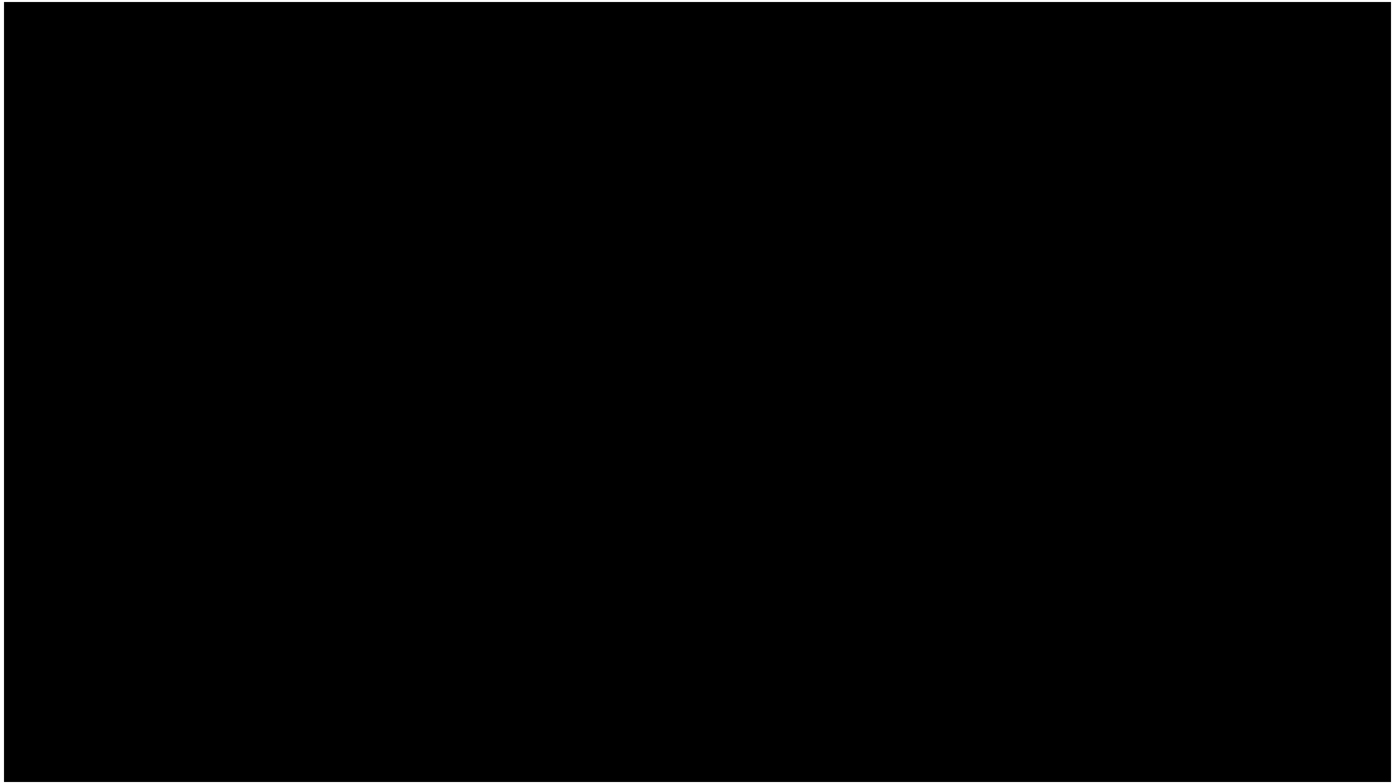


Self-Organization

- Biology: **Spontaneous protein folding**



- Biology: **Spontaneous formation of lipid bilayers**

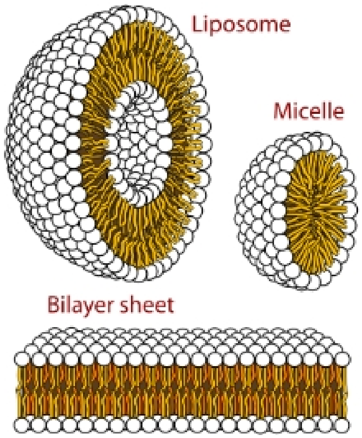


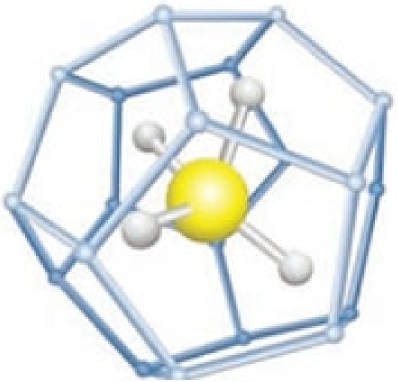
- Biology: **Spontaneous formation of lipid bilayers**

  - ✓ 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 configur-ations**, finding ones that **maximize total entropy** (minimize total free energy), that get "locked in" when the available energy disperses into the environment





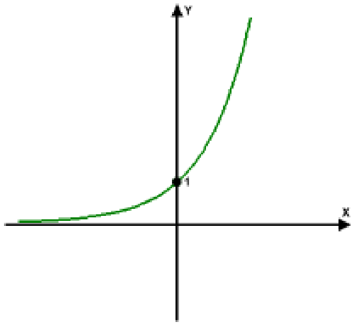
Deeper Understanding of the Second Law

- 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:

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

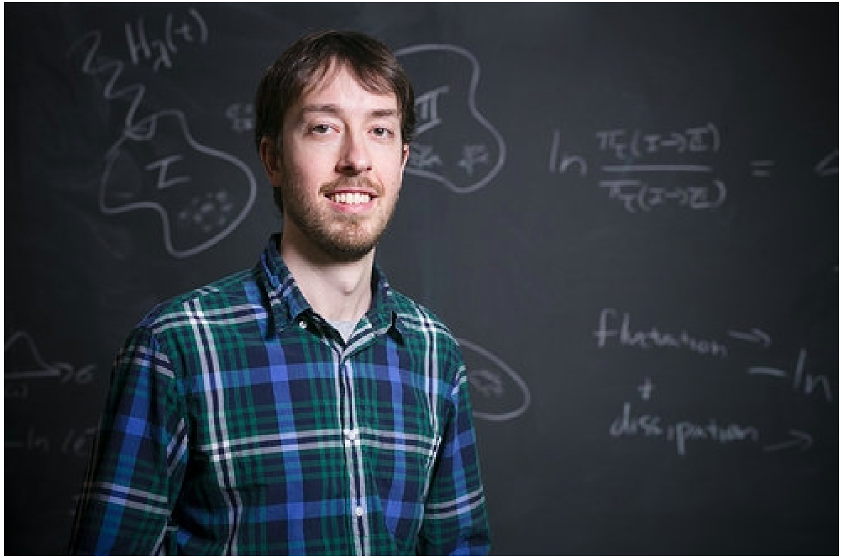


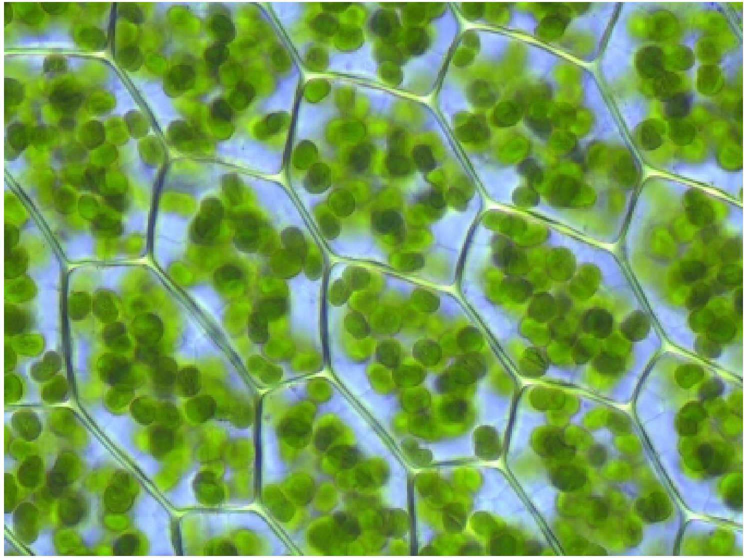
  - ✓ In words:
    - **Small** fluctuations are **equally likely** to be **positive** or **negative**
    - **Large** fluctuations are **almost always positive**

  - ✓ ...but **on average**, the Second Law **is** strictly true: $\langle \Delta S \rangle \geq 0$.

- 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 **<u>may</u>** 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**:

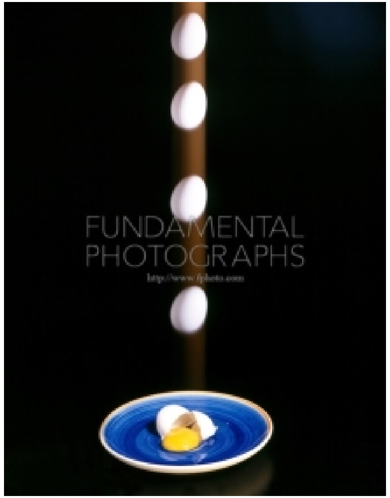
    - "[England has taken] a very brave and very important step…the 'big hope' is that he has identified the underlying physical principle driving the origin and evolution of life"—Alexander Grosberg (physics professor at NYU)

    - "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)

- 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.

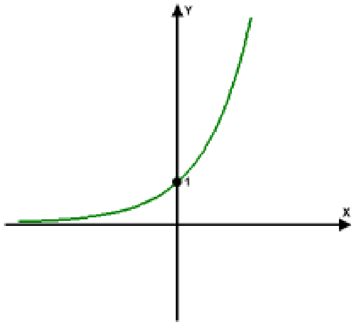
  ✓ But living organisms are **far-from-equilibrium** systems interacting with their environment, and **strongly driven** by external sources of energy (e.g., plant blasted with sunlight). Before work like Crooks', and others, physicists didn't have the mathematical tools to understand such systems. **Now they do**.



- 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.

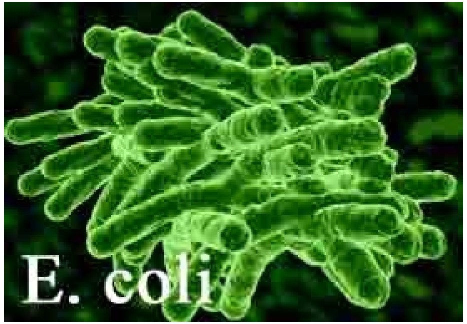
✓ Or: The **most probable** outcomes are the ones that, on the way to getting there, **increase the entropy of the universe the most**

- 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."

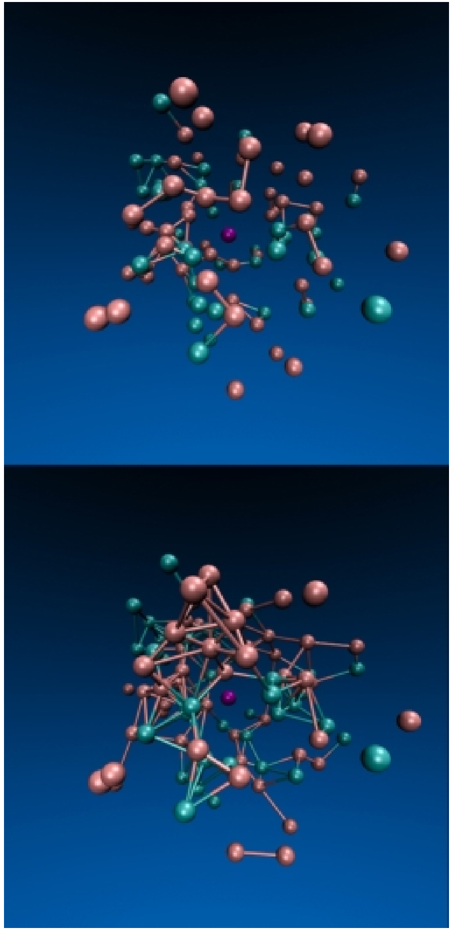


Why is there life?

- 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**]."

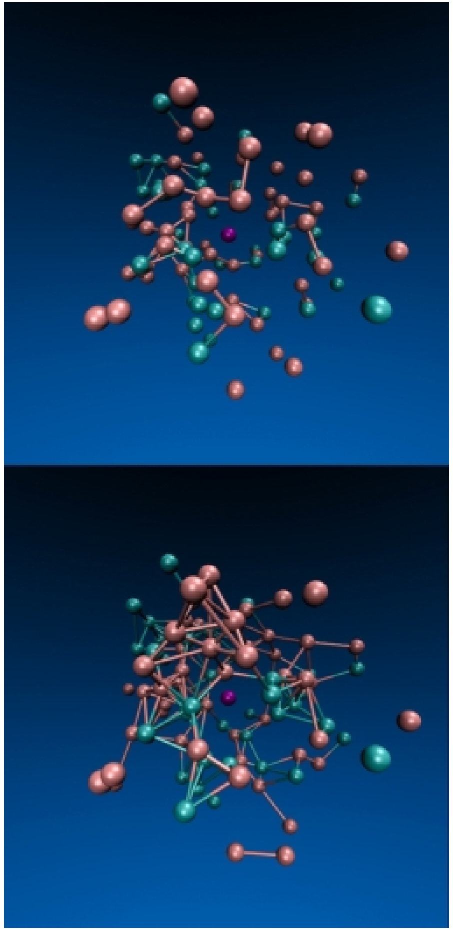
  ✓ **Analogy:** the length of the ropes of a swing will **spontaneously** adjust themselves so the **natural frequency** of the swing matches the **driving frequency**, allowing the swing to absorb (and later dissipate) the most energy (!)



- 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)**.



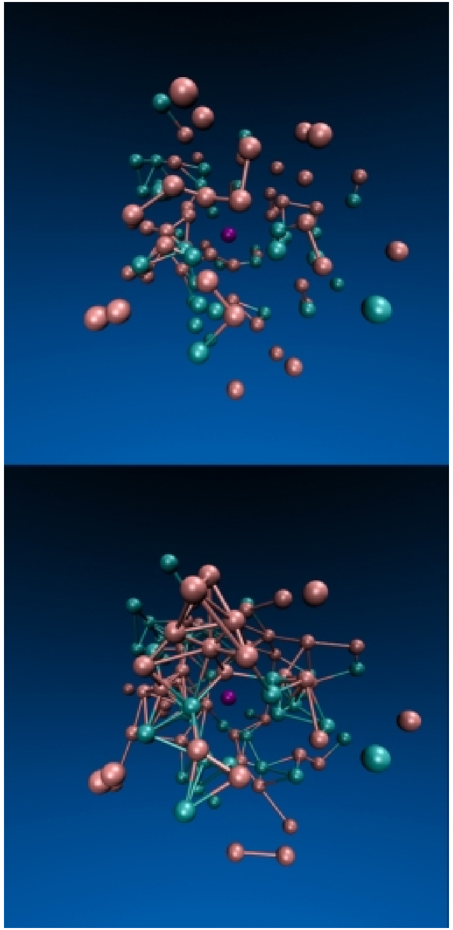
- Speculation: "[Dissipation-Driven Adaptation of Matter]"

  ✓ 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**.



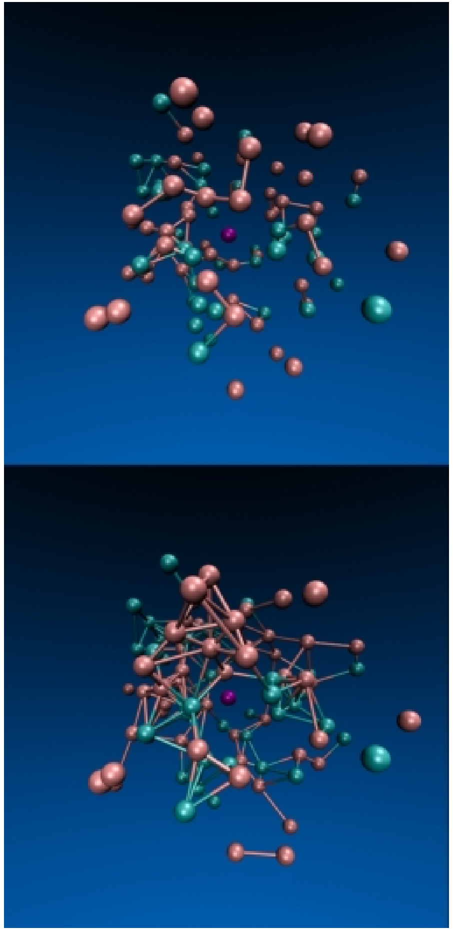
- Speculation: "Dissipation-Driven Adaptation of Matter"

  ✓ 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".

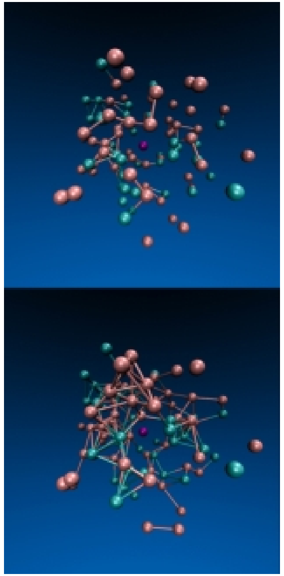
  ○ "There may be many examples of 'well-adapted' structures that did not have parents." (**Non-Darwinian adaptation**…)

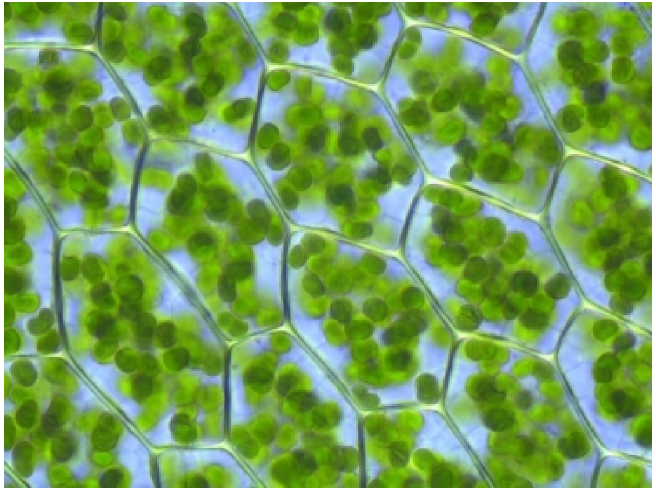


Why is there life?

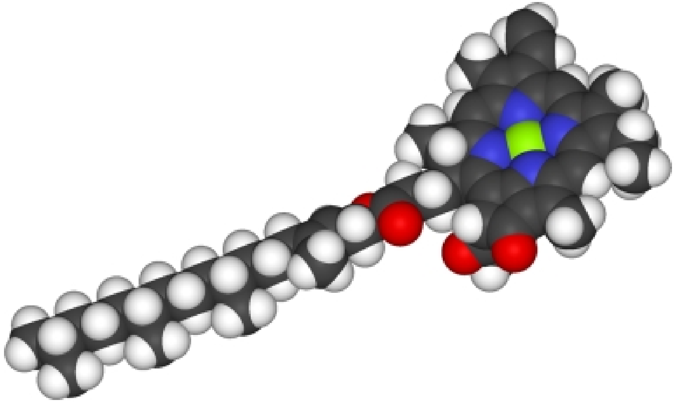
- Example: Plants/Photosynthesis

  ✓ 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."**





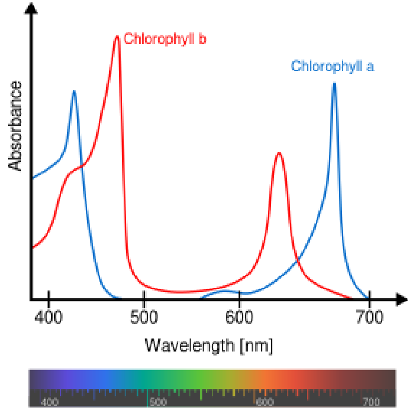
Chloroplasts in plant cells



Chlorophyll molecule inside chloroplast

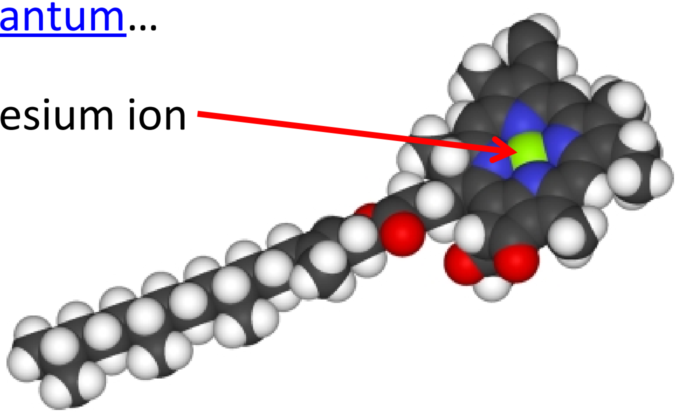
Why is there life?

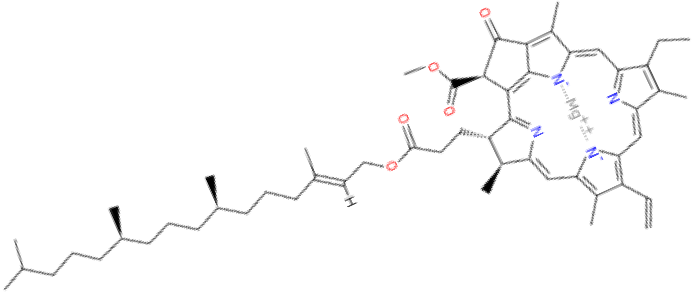
- Example: Plants/Photosynthesis



✓ 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]…

Magnesium ion





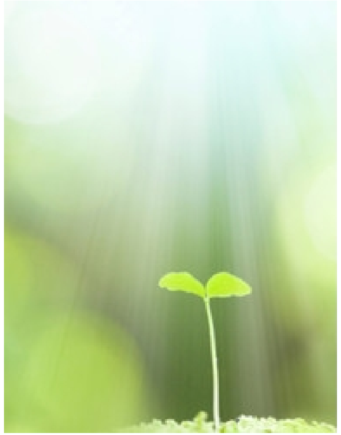
- Example: Plants/Photosynthesis

  ✓ 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):

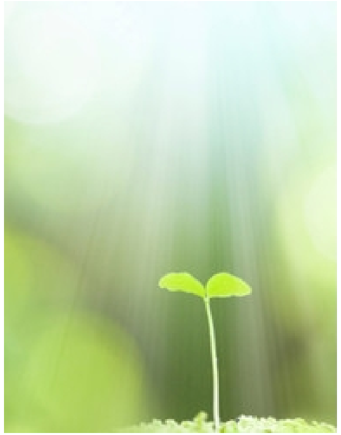
$$\underset{\text{Carbon dioxide}}{6CO_2} + \underset{\text{Water}}{6H_2O} \xrightarrow{\text{Light}} \underset{\text{Sugar}}{C_6H_{12}O_6} + \underset{\text{Oxygen}}{6O_2}$$

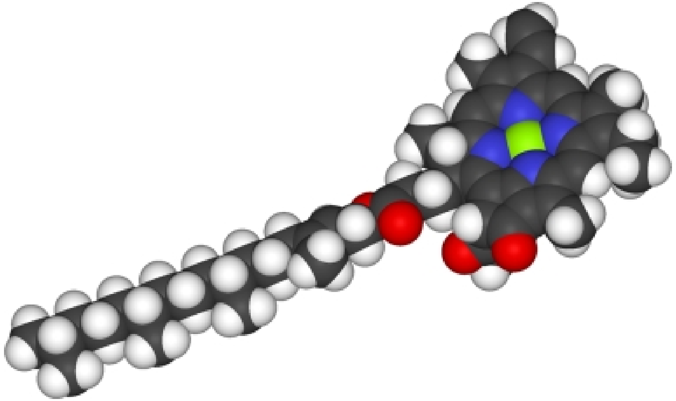
  ✓ The rest is **dissipated in the environment** as waste heat. This is **crucial**: The resulting **increase** in entropy of the environment is precisely what allows the plant to build and maintain **low entropy structures** (like the chlorin ring).

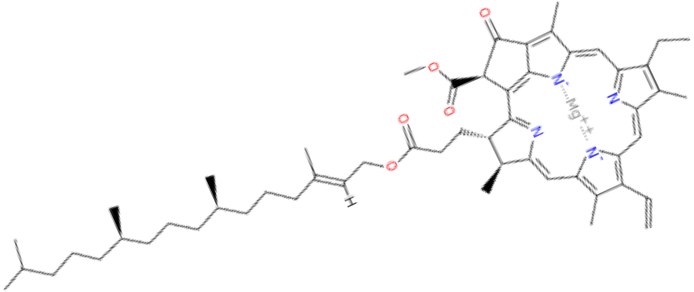


- Example: Plants/Photosynthesis

    ✓ 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!!)



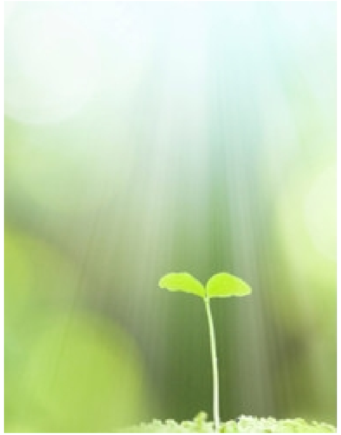


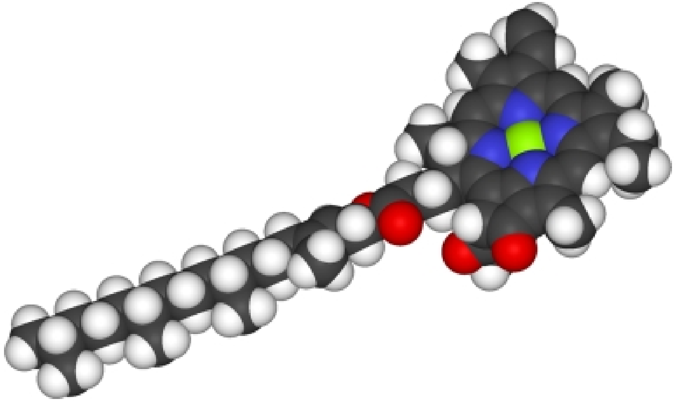


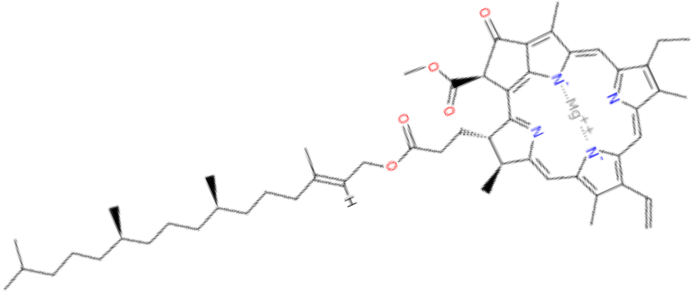
Why is there life?

- 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.



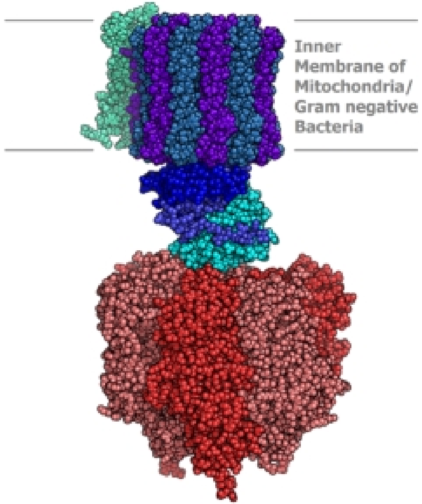


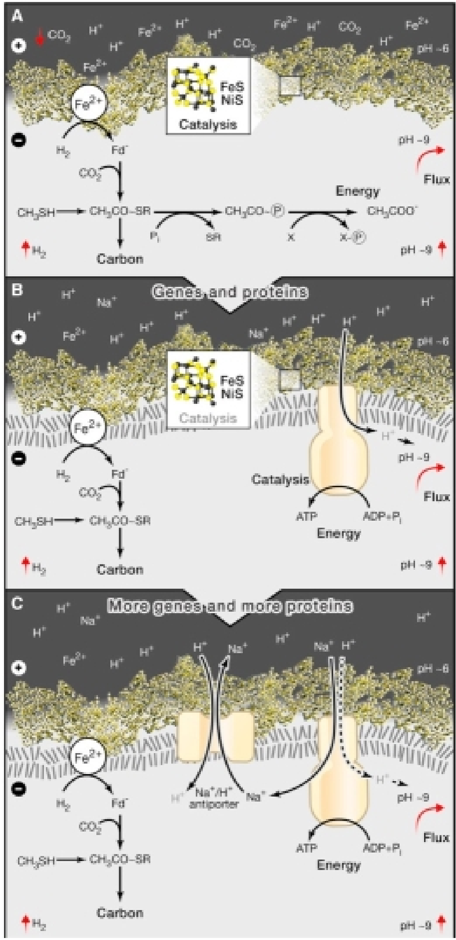


Why is there life?

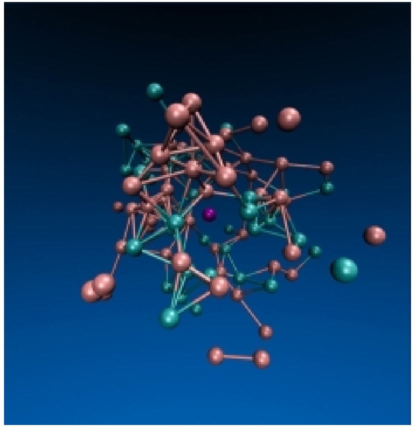
- Could the **ATP synthase** be another (more complex) example of an ordered structure that **spontaneously evolved** by “dissipation-driven adaptation of matter” to allow proto-cells to harness (and dissipate) more energy from the natural proton gradient near deep-sea hydrothermal vents? (Speculation!!)

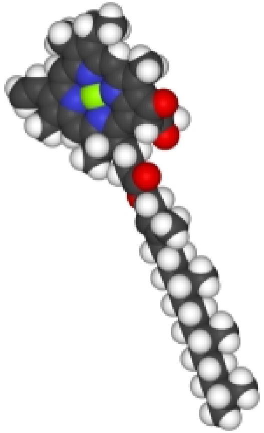
- This could explain how the top picture evolved to the middle picture without replication of cells and Darwinian natural selection (Recall England: “**There may be many examples of ‘well-adapted’ structures that did not have parents**.”)





- 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”.

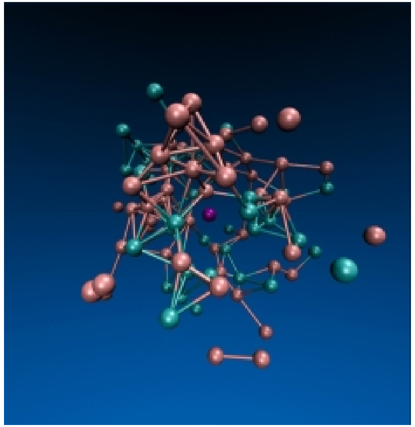
Why is there life?

- 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**."

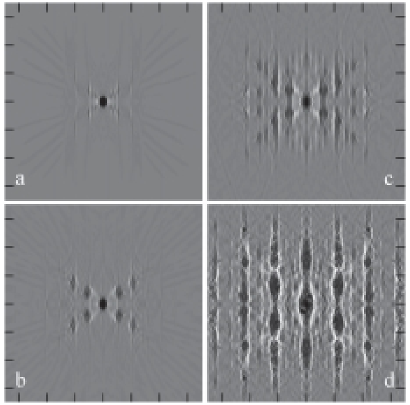
  ✓ This is arguably plausible, but still highly speculative. It's exciting, though, because it **might** explain, for very general reasons tied to the basic physics of the universe, **why** there is life!

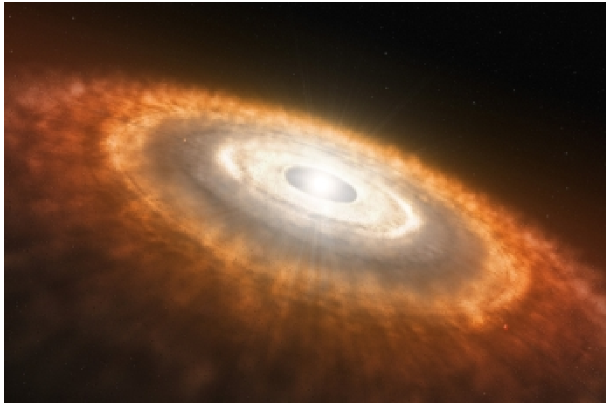


- Applications Beyond Life:

✓ 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.





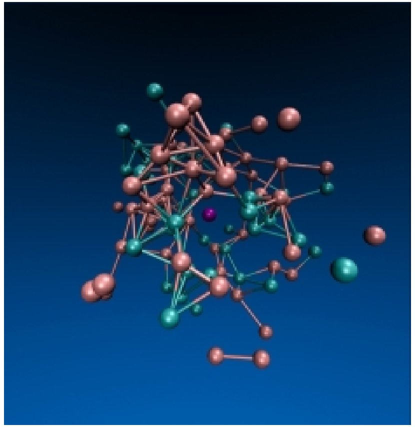
Vortices in a shear flow **spontaneously replicate** by absorbing energy from the surrounding fluid. This has applications to “dead zones” in protoplanetary disks, and may play a role in star and planet formation.

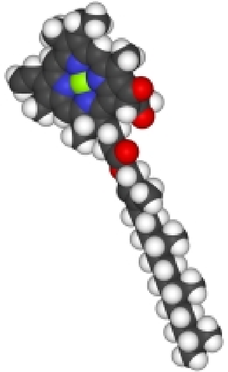
Summary: Dissipation-Driven Adaptation of Matter

- **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.

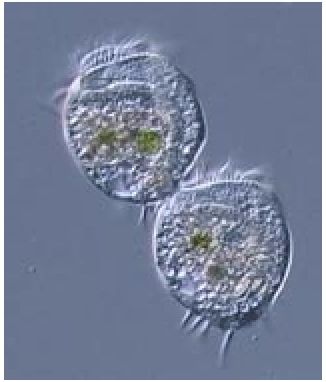
- While **still speculative**, there is reason to hope that it may be a fundamental principle behind a wide range of phenomena in nature, including possibly the **origin and evolution of life**. It’s a promising idea that helps scientists focus attention in a potentially fruitful direction. But of course **it might be wrong**…

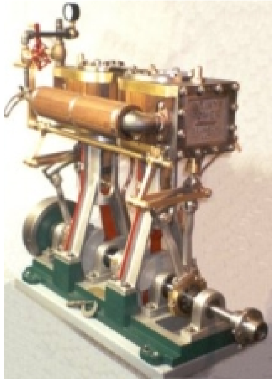




Summary: The Importance of Thermodynamics

- **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 <u>inevitable consequence</u> of thermodynamics (?)**"



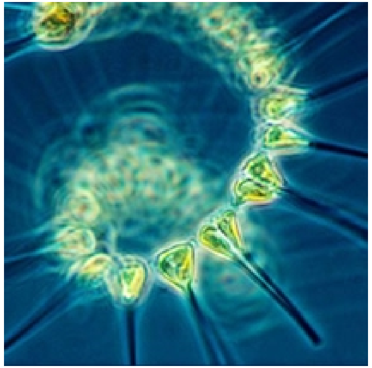


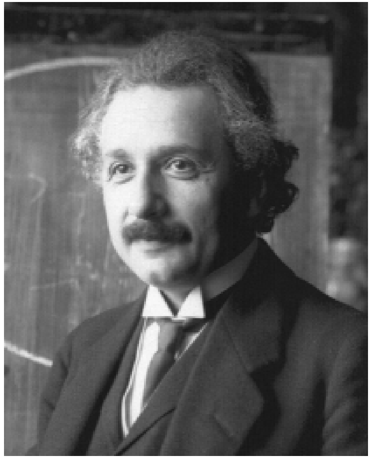
Summary: The Importance of Thermodynamics

- 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.”





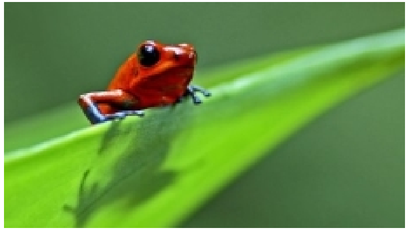
- Comments on thermodynamics:

  ✓ 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…

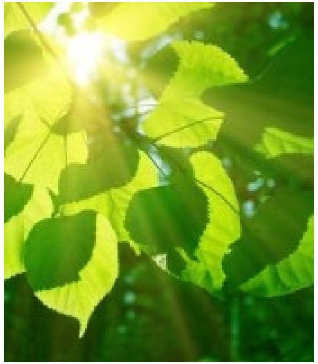


Back to: **Why do we eat?**

- To get **energy**!

- But by the 1st 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.



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.)

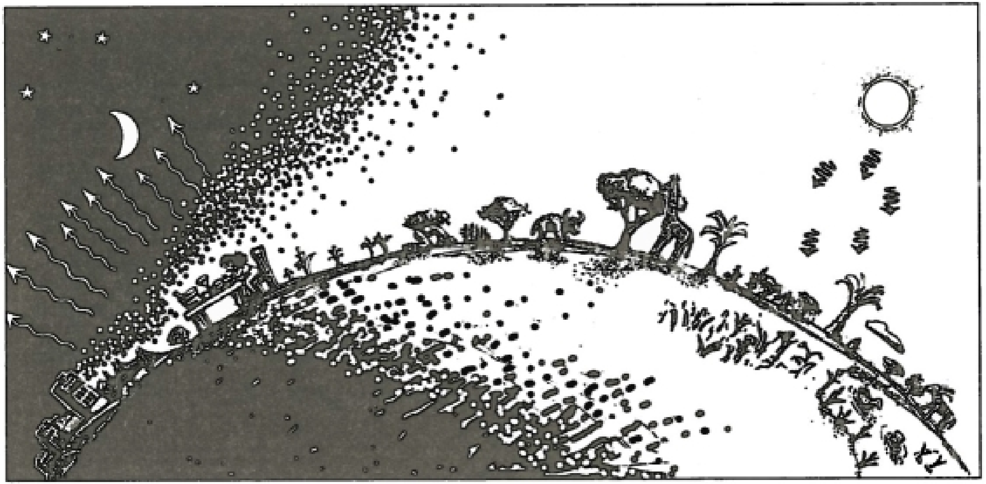
- Where does this free energy **come from**? There are **two sources**:

  - ✓ The **Sun** (or other stars in the case of extra-terrestrial life)

  - ✓ The **Earth** (chemical and thermal **dis**equilibrium of a planet)

Example: Free energy from the Sun

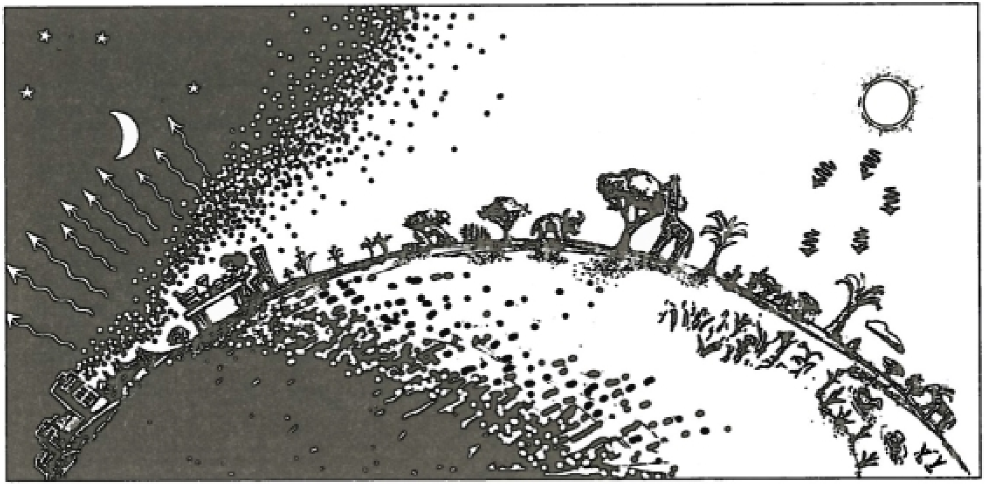
- ✓ The Earth absorbs **high energy** (hot) photons from the Sun, warming its surface
- ✓ On average, the Earth **does not get hotter** (notwithstanding global warming, etc.)
- ✓ Thus, the Earth must radiate exactly the same amount of energy back into space, but now in the form of **lower energy** (cooler)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



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

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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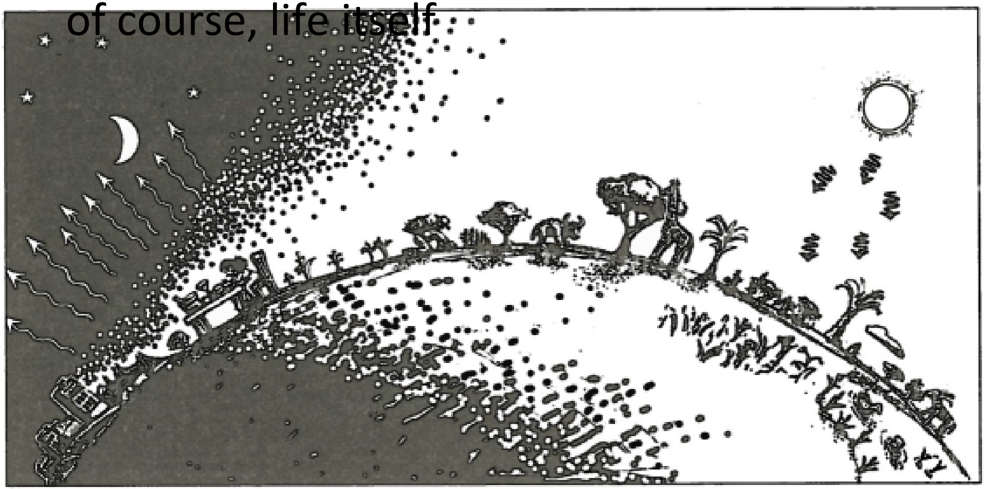
Example: Free energy from the Sun

- ✓ 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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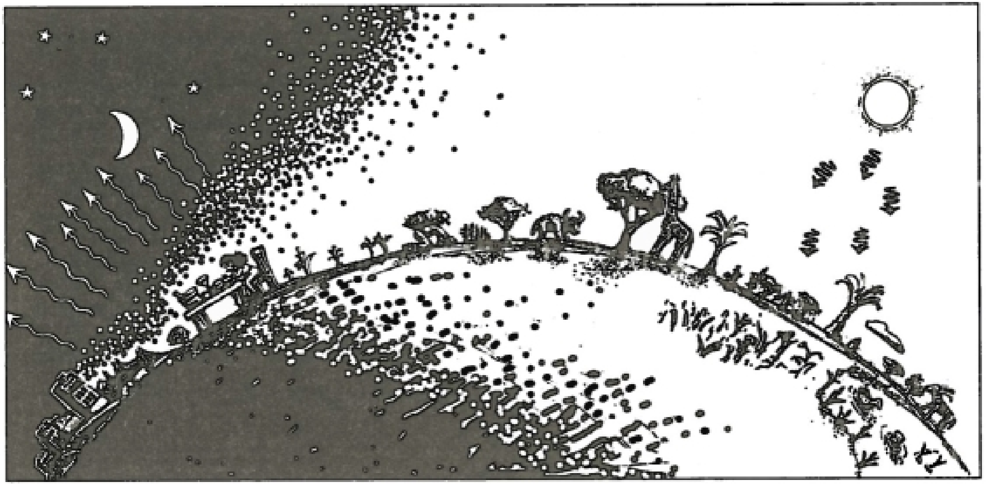
Example: Free energy from the Sun

- ✓ 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?



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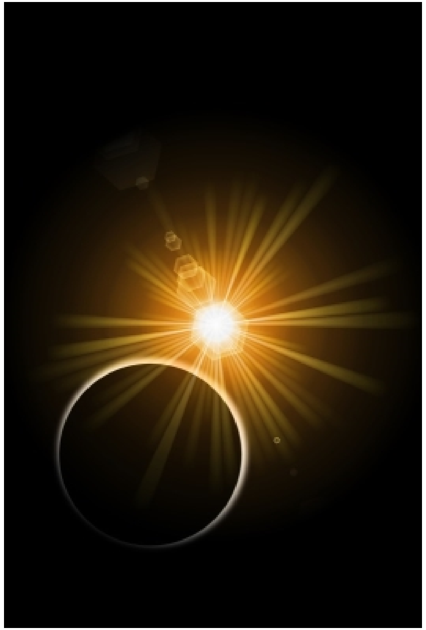
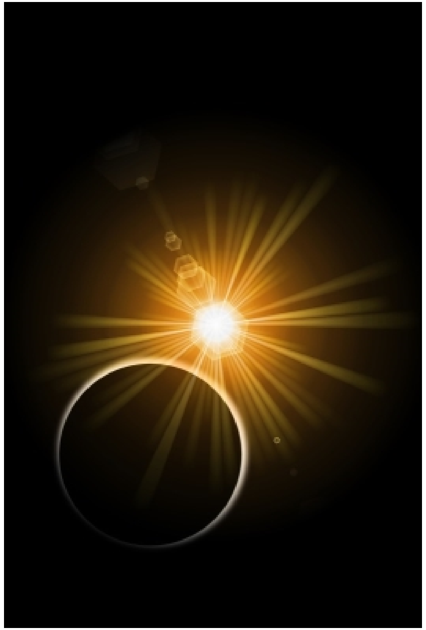
Question 1: Why is the Sun a **hot spot**?



- ✓ 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**.

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