From Steaming Cups to Cosmic Evolution: The Hidden Force of Entropy

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Introduction

Why does tea go cold? It seems simple yet the answer delves deep into a fundamental concept which governs the behaviour of our universe. Anyone who has left a warm tea unoccupied will have observed its inevitable cooling, seemingly of its own accord. But what's really at play here is the unstoppable force of entropy.

Formation of a tropical storm generated by low entropy. (Metych 2023)

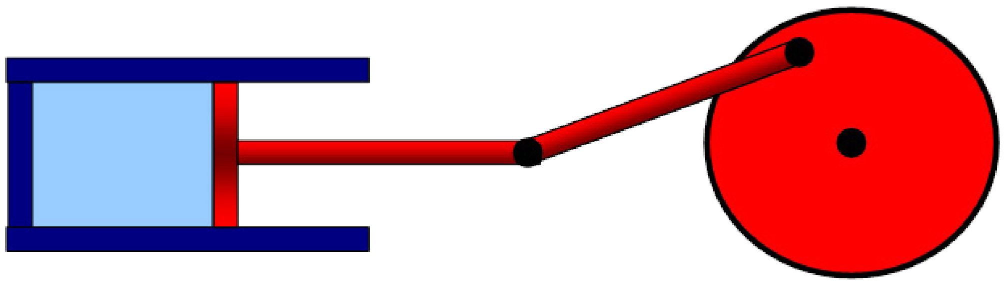
Emerging from early steam engine thermodynamics, entropy measures the spread of energy in a system. It is a fundamental concept for understanding heat in modern physics, but recently entropy has extended into various disciplines, becoming more than just the second law of thermodynamics.

Entropy governs everything from molecular collisions to humongous storms, from the universe's beginning through its entire evolution to its inevitable end. It may, in fact, determine the direction of time and even be the reason that life exists.

In this article, I will argue that the role of entropy in science extends far beyond its thermodynamic roots. To do this I will first outline the concept of entropy, detailing its origin in thermodynamics. Then I will investigate three examples where entropy has played a pivotal role in advancing scientific understanding.

History of the Heat Engine

The science of heat engines began long before the nature of heat was fully understood (Chandler, 2010). In 1824, Sadi Carnot first showed that any heat engine has a theoretical maximum efficiency that depended on the temperature difference between the hottest steam and the cooling water (see equation below).



The Carnot engine: an ideal engine where a cylinder filled with hot gas is rapidly condensed by a jet of cold water doing mechanical work on a piston (Fowler 2017).

In Carnot's time, steam engines could reach temperatures up to 100 degrees Celsius. So, their theoretical maximum efficiency was 27%, but their real efficiency was more like 3% (Fowler, 2017). This is because real engines experience friction and dissipate heat to the environment. So, for just as much heat going in, less energy ends up in the flywheel. The rest is spread out over the walls of the cylinder and is radiated out into the environment.

When energy spreads out like this, it is impossible to get it back. So, this process is irreversible. The total amount of energy didn't change, but it became less usable. Therefore, energy is most usable when it is concentrated and less usable when it's spread out.

$$\eta_{Carnot} = 1 - \frac{T_{Cold}}{T_{Hot}}$$

Carnot's equation

↓

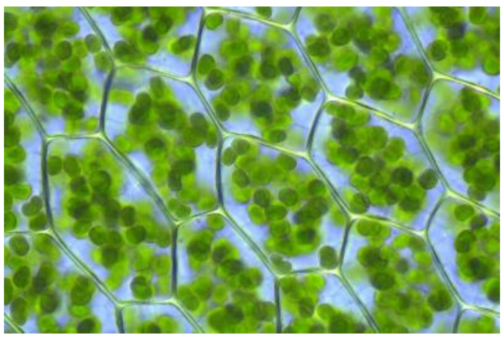
$$1 - \frac{273K}{373K} = 0.27$$

Efficiency of Engines in Carnot's time

Decades later, German physicist, Rudolf Clausius, studied Carnot's engine, and produced a way to measure how spread out the energy is. He called this quantity entropy (Clausius 1879). When all energy is concentrated in the hot gas, there is low entropy, but as energy spreads to the surroundings entropy increases. This means the same amount of energy is present, but in this more dispersed form, it is less available to do work.

Life on Earth

Earth is in the Goldilocks zone for life. The sun is essential for living organisms on Earth, but what does it actually give us?



Chloroplast in plant cells: the foundation for photosynthesis.

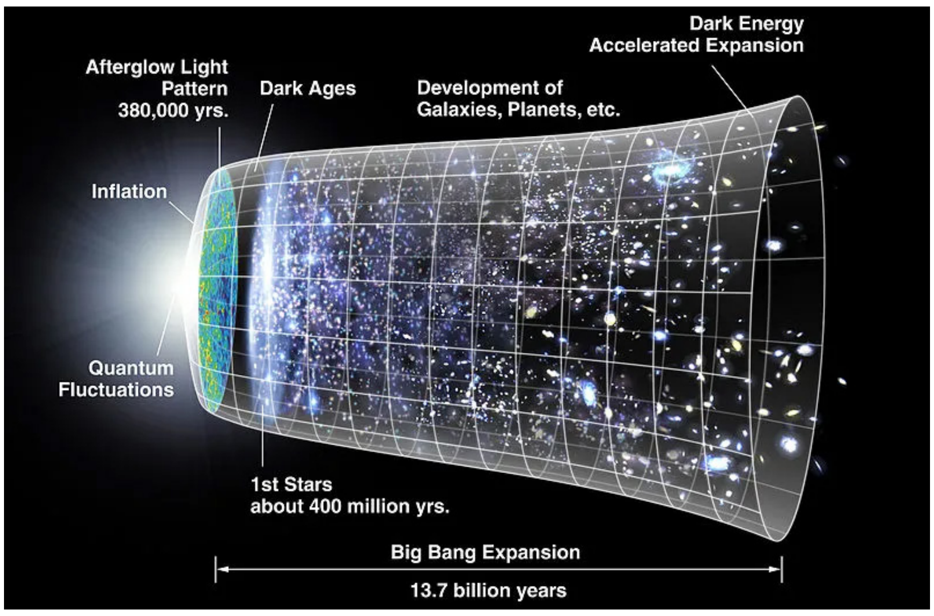
Life in its simplest form takes the concentrated packets of energy from the sun (photons) and dissipates them in less concentrated forms. A plant, for example, absorbs extremely energetic sunlight, uses it to build sugars, and ejects infrared light (Schrodinger 2012). This ties into the second law of thermodynamics which states that entropy in a closed system will tend to increase over time. Chemical reactions, celestial processes and natural life all increase the total entropy of the universe, spreading energy into thermal stores.

Without a source of low-entropy energy, life on Earth would not be possible. Because of this, it has been suggested that life itself may be a consequence of the second law of thermodynamics.

When energy flows through a system, it can organise matter and lead to the emergence of complex structures, such as living organisms, that are better at dissipating energy and increasing entropy (England 2015). According to physicist Jeremy England (2013), ‘you start with a random clump of atoms, and if you shine light on it for long enough it should not be surprising that you get a plant’. Here England proposes that if there is a constant stream of concentrated energy, this favours structures that dissipate that energy and over time, this results in better and better energy dissipators until eventually you get life (Schneider & Kay 1994).

Whilst this builds on Darwin's theory of evolution and offers a novel perspective supported by formulae derived from established physics (Wolchover 2014), other scientific explanations for the origin of life - such as the deep-sea vent hypothesis (see Martin et al. 2008) - are equally viable. As a result, more research is needed to establish the validity of England's ideas.

The Direction of Time and the End of the Universe



The increasing entropy of the universe since the big bang

Since the Big Bang (the lowest state of entropy known), entropy has been ever-increasing as space-time expands (Carroll 2022). Now, regarding the direction of time, it is observed that things generally go from being ordered to being disordered. For example, an ice cube melts and spreads out into water, but water doesn't spontaneously turn into an ice cube in a warm room. This is because it's much more likely for things to become more disordered over time, following the arrow of increasing entropy (Hawking, 1985). As suggested by Sean Carroll (2008) we are constantly going from unlikely to more likely states: an irreversible process which divides the past and present, directing the behaviour of the universe. This a simple and, therefore, appealing concept of time.

This is expected to continue until eventually, energy gets spread out so completely that nothing interesting will ever happen again. This is the heat death of the universe. In the distant future, more than 10^100 years from now, after the last black hole has evaporated (Bekenstein, 1972), the universe will be in its most probable state. Now, even on large scales, you would not be able to tell the difference between time moving forwards or backwards, and the arrow of time itself would disappear.

That's right, entropy is not only stopping us from turning omelette into eggs, but it is also to blame for ending the entire universe. Unfortunately, there is nothing we can do to prevent this, in fact, everything we do increases entropy and accelerates the inevitable ending. The best way to save the universe is by doing absolutely nothing!

Conclusion

From the everyday event of tea cooling to the vast changes in the cosmos, entropy stands out as a key player in our universe. Beginning with steam engines it now influences many fields of science.

Entropy isn't just about heat; it affects time, life's complexity, and even the fate of the universe. It's a natural law that governs the way things unfold, from tiny particles to entire galaxies.

Words: 999

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