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ENTROPY: CAN WE TURN BACK TIME?



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Visualization of
the arrow of time

In the infinite dance of the Universe, two of the most fascinating concepts are *entropy* and the *arrow of time*.

These notions are attempts at making sense of the inexorable trend towards disorder in our universe, as well as the irreversible, one-way nature of time.

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It is hard to ignore today's pervasive fixation on being young. After all, who does not desire smooth, youthful skin, strength emanating from every muscle, and an insatiable curiosity to explore the world? All these are hallmarks of that unique stage of life we call "youth." But does the natural world share our fascination? Can it endure indefinitely – or is our universe also perhaps subject to the relentless march of time and irreversible decay?

The Measure of Disorder

To discuss the notion of *entropy*, we first need to pin down a few key concepts. One of these is thermodynamics – a branch of physics that investigates how energy behaves in various physical and chemical processes. Thermodynamics provides a way to model the transformations of energy within systems – primarily thermal changes but also energy released or absorbed during chemical reactions, transformations involving ions or phase transitions like melting and boiling, and even nuclear reactions and electricity consumption.

With wide-ranging applications, thermodynamics has paved the way to the invention of such engineering wonders as the combustion engine, turbines, refrigeration systems, and other thermal devices. It helps us to better understand chemical reactions and to design chemical processes, while in materials science, it aids in analyzing the properties of materials and their responses to temperature and pressure. In

meteorology, it helps explain atmospheric phenomena like cloud formation, precipitation, and wind patterns, while in biology, it elucidates processes within living organisms, such as respiration and photosynthesis.

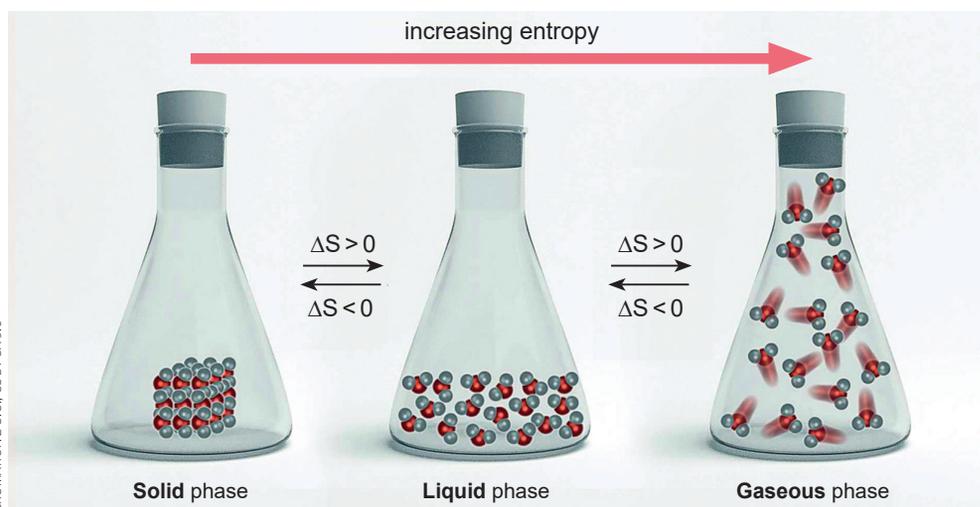
Importantly for this article, thermodynamics also plays a pivotal role in our comprehension of the universe and its evolution. Its principles define how energy and matter behave across time and space, offering insights into their past, present, and future states.

Entropy is one of the fundamental concepts in physics. Denoted by the letter S , entropy quantifies the degree of disorder within a system. Essentially, higher entropy indicates greater disorder. In thermodynamics, entropy measures the spread of energy throughout a system. Mathematically, entropy can be defined in various ways, with one of the most common expressions being Boltzmann's formula:

$$S = k \cdot \ln(W)$$

Where k represents the Boltzmann constant ($k = 1.38 \times 10^{-23}$ J/K), and W denotes the number of possible microstates of the system. The term "microstates" refers to the different configurations in which molecules within the system can arrange themselves. A larger number of microstates corresponds to a more disordered state. Entropy is closely tied to the second law of thermodynamics, which stipulates that the entropy of a closed system cannot decrease in a spontaneous process. This principle implies that all natural processes tend to increase disorder over time.

Physical formulas can sometimes be hard to grasp, so it's useful to provide a few examples to better understand what entropy is. Picture a room filled with books. Initially, the school librarian neatly arranges all the volumes on the shelves. The room then has low entropy, because the system is well-organized. However, when a group of children enters the library and each picks up several books, trying to decide which



Changes in entropy depending on the state of matter

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ones to read, they often place them back in different spots on the shelves or just leave them lying on the floor. The entropy of the room increases as the system becomes more disordered.

Another example is provided by a piece of iron exposed to moisture in the air, causing it to corrode or rust. This process is an irreversible chemical reaction that leads to an increase in the metal's entropy. Or, on a cosmic scale, consider a star generating energy through nuclear fusion. The star gradually dies as it consumes its nuclear fuel, leading to an increase in its entropy.

A one-way street

In 1927, the British astrophysicist Arthur Eddington introduced and popularized the concept of the *arrow of time* to describe the evolution direction of an isolated system, where entropy uniformly increases. This

logical arrow of time. It is based on the observation that the Universe is expanding – galaxies are moving away from each other, space is becoming increasingly sparse. This expansion process is viewed as the reason behind the arrow of time.

Another intriguing perspective on the arrow of time is the psychological arrow of time. According to this theory, we ourselves subjectively experience the passage of time. The past is perceived as finite and unchanging, while the future is seen as open and uncertain. In essence, we remember events from the past but cannot predict what will happen in the future. This subjective experience is fundamental to our understanding of time and plays a significant role in many aspects of our lives. While we can remember events from the past, we cannot remember the future. This is because memory involves constructing and storing information about past events. Based on our experiences from the past, we can plan future actions, assuming that the future will unfold similarly to the past. This is why narratives about our lives typically follow a linear structure, going from past to future – it helps us to comprehend and remember events more effectively when they are presented chronologically.

Reversing the process

Now let's consider whether entropy always increases and if there is any possibility to reverse this process. It turns out that entropy *can* decrease locally – in other words, in certain systems and processes, we observe increased orderliness and reduced chaos. There are numerous examples of such local entropy reductions in nature and technology. For example, when a liquid cools below its melting point, its molecules form together into a regular crystalline structure, reducing entropy because molecules in a crystal are more ordered than in a liquid state. A refrigerator, in turn, works by removing heat from inside and transferring it to the surroundings, consuming electricity but reducing the entropy inside because heat moves from lower to higher temperature areas. Unfortunately, any local entropy reduction always increases entropy somewhere else. According to the second law of thermodynamics, the total entropy of a closed system always increases. This means that while we can locally reduce entropy in one place, we can never reduce the total entropy of the Universe.

From the perspective of physics, therefore, youth – a stage of intense development and dynamic potential – emerges as a fascinating intersection of both entropy and the arrow of time. It's a period characterized by both biological and emotional growth, alongside an increase in chaos and uncertainty. Youth is a time when individuals confront the inevitable passage of time, yet also gain strength and determination to shape their own futures. ■

The arrow of time is not an absolute concept. Some physical theories, such as Einstein's theory of relativity, suggest that time might be relative and time travel might actually be possible.

implies the existence of a distinct direction in which time flows and thereby, a fundamental difference (independent of the observer) between the past and the future – hence, between two possible directions of time's passage. Therefore, the arrow of time represents the fundamental asymmetry of time itself. The intuitive notion underlying the arrow of time is that time is irreversible, always flowing from the past to the future. This stands as one of the fundamental properties of time as a dimension. The arrow of time is a crucial topic for science. If we were to dismiss the notion that one direction of the succession of events is special, the difference between the initial and final states of things – as inherently experienced by all human beings witnessing the passage of time – would essentially be deemed unreal and illusory.

There are various theories that attempt to explain the arrow of time, but none of them are universally accepted. Some of the most prominent theories describe the thermodynamic arrow of time. This theory is rooted in the second law of thermodynamics: the entropy (a measure of disorder) of a closed system always increases. This implies that the Universe progresses from a state of low entropy (the Big Bang) to a state of high entropy (the heat death of the Universe). Another theory considers the cosmo-

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