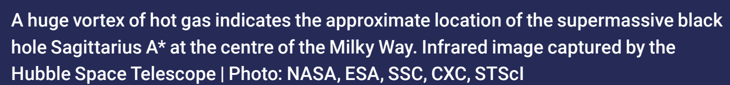
INFORMATION PHYSICS, OR WHY DO WE NEED ENTROPY?

The term *entropy* was first used in 1865 by the German physicist and mathematician Rudolf Clausius. It derives from the Greek *tropē (τροπή)* meaning turn, change, transformation. The very etymology of the term suggests that it is a concept describing the direction and nature of the processes taking place.


A huge vortex of hot gas indicates the approximate location of the supermassive black hole Sagittarius A* at the centre of the Milky Way. Infrared image captured by the Hubble Space Telescope | Photo: NASA, ESA, SSC, CXC, STScl

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IT ALL STARTED WITH THERMODYNAMICS

Entropy appeared with the birth of thermodynamics – a field of physics that arose in response to the needs of the Industrial Revolution. The development of steam and heat engines the 19th century posed some new challenges for science. The existing laws of classical mechanics – developed since ancient times and then formalised in the 17th century by Isaac Newton – proved insufficient to describe the processes involved in heat transfer and the conversion of thermal energy into mechanical work. This led to the emergence of thermodynamics – a branch of physics dealing with the description of thermal processes, energy balance, and the limits of energy conversion efficiency. Its development led to the formulation of fundamental laws. The zeroth law introduced the concepts of temperature and thermal equilibrium: if two systems have the same temperature, they remain in equilibrium. The first law of thermodynamics is the law of conservation of energy. The second law of thermodynamics, however, was of key importance – and it was in this law that the concept of entropy first appeared.

'The second law can be formulated in many ways', explains Prof. Jerzy Dajka, a physicist at the Institute of Physics of the University of Silesia in Katowice. 'One of the most vivid descriptions states that it is impossible to build a heat engine that would draw heat from only one thermostat and convert it entirely into work. In other words, the mere presence of thermal energy is not enough to perform useful work. A classic example involves a ship sailing on the ocean. Water contains a huge amount of internal energy, yet we are unable to extract it and use it directly to power the ship. For the ship to sail, a second thermostat and heat transfer between at least two reservoirs of different temperatures are necessary.

From this perspective, entropy appears as a quantity that orders the direction of thermodynamic processes. In classical thermodynamics, it is a state function whose change allows us to distinguish between possible and impossible processes. According to the second law, the entropy of an isolated system – i.e. one that exchanges neither energy nor matter with its surroundings – never decreases. It may remain constant (in ideally reversible processes), but in real processes it has to increase.

The existence of entropy has its consequences. It determines the arrow of time in macroscopic physics, explaining why certain processes occur spontaneously in only one direction.

'Let's imagine two photographs. One shows a broken egg and the other shows an intact egg. Intuitively, we can all tell which photo was taken first', explains Jerzy Dajka. 'Entropy is a quantity that allows us to order the chronology of events. In the case of an unbroken egg, entropy is lower, and in the case of a broken egg, it is higher, and thus we can see that entropy is related to disorder. In other words, it is a quantity that we can use to estimate disorder in a system. What is more, we know that this disorder can only increase. That is not all: systems are not capable of ordering themselves, which means that the broken egg cannot return to its pre-broken state on its own. It was only with the birth of statistical mechanics that we were able to link entropy to the statistical properties of complex systems, and the famous entropy formula describing it is inscribed on the tombstone of its discoverer – the great Ludwig Boltzmann'.

WHAT DOES ENTROPY HAVE TO DO WITH INFORMATION?

Although the concept of entropy was born in relation to heat engines and energy processes, over time it turned out to have a much broader meaning – extending to information theory, computer science, biology, and even cosmology.

In the 1940s, American engineer and mathematician Claude Shannon created the mathematical foundations of information theory. In his 1948 paper, he introduced a measure of uncertainty associated with the transmission of information (signal) from point A to point B, which he deliberately called entropy. In Claude Shannon's view, entropy emerged as a measure of information encoding and transmission. Shannon considered the source of information to be a random process that generates symbols – for example, letters of the alphabet – with specific probabilities. He showed that information entropy is a measure of the average amount of information per symbol and, at the same time, a measure of the unpredictability of such a process. If all letters appear with equal probability, entropy is at its maximum; on the other hand, if some symbols are much more

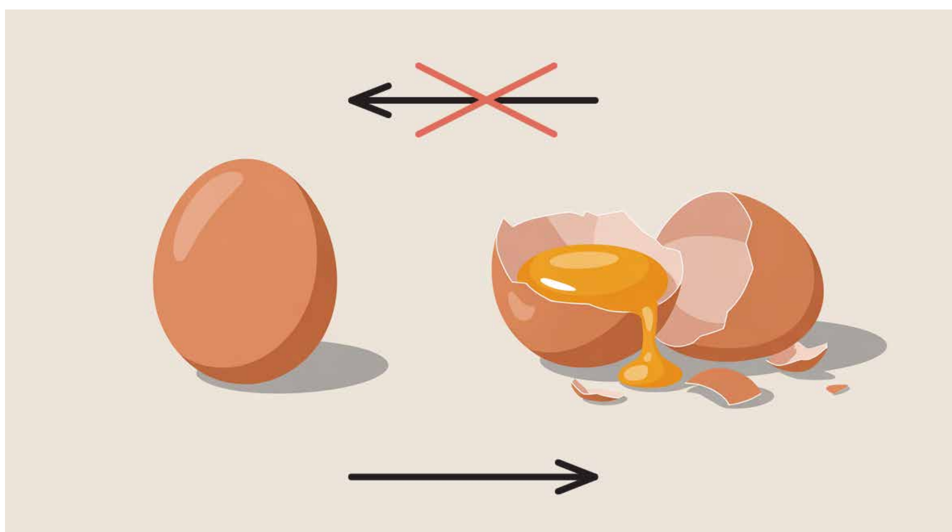

Photo: Freepik AI

frequent than others, entropy decreases, which means that the message contains less information per symbol. It is this quantity that determines the limit of data compression: entropy determines the minimum average length of code needed to record a lossless message. In this way, Shannon linked the abstract concept of information to the practical problems of encoding, transmission and effective determination of the information capacity of communication channels.

'Entropy and its various variations began to be used in encoding, decoding, and transmission of information. Cryptography is a special case of these issues', adds the physicist. 'One type of entropy, mutual entropy, plays a key role in cryptography as a measure of the information that can be obtained from encrypted text. This leads to a number of interesting entropy-based security criteria and directly translates into the resistance of a cryptographic system to attacks'.

Entropy can also be a measure of the behaviour of dynamic processes, i.e. those that occur over time. From the point of view of physics, a very important feature of such processes is their ergodicity when the observation of a single system over a long period of time can be replaced by a shorter observation of many of its copies.

'Entropy-based measures can be used in issues related to risk assessment, prediction of future behaviour and, above all, in distinguishing between processes that are truly chaotic and those that have a certain order or random component', explains the scientist.

In this sense, entropy no longer describes disorder in the colloquial sense, but rather the degree of our ignorance about the state of the system. The more possible configurations are consistent with the observed data, the greater the entropy – and thus the less information we actually have. In a sense, information turns out to be negative entropy: its increase means a reduction in uncertainty.

INFORMATION IS ALSO SUBJECT TO THE LAWS

Physics shows that information processing has tangible energy consequences. The Landauer principle, formulated in 1961, plays a key role here, according to which the removal of even a single bit of information from the memory of a physical system must be associated with a minimum release of heat, and thus with an increase in the entropy of the environment. In other words, information is not an abstract entity detached from matter – it must always be stored, processed, and deleted in a physical medium subject to the laws of thermodynamics.

'In fact, every phenomenon we encounter in the physical world is a thermodynamic process', explains the physicist. 'Therefore, all phenomena in which entropy would spontaneously decrease must be rejected as non-physical. Otherwise, we would be dealing with a perpetual motion machine of the second kind'.

Taking this into account makes the second law of thermodynamics take on a new meaning. Not only does it limit the efficiency of heat engines but it also sets limits on information processing. Every calculation, every logical operation, and every act of forgetting has its cost. Contemporary research shows that these limits are beginning to have practical significance in quantum computers.

Thus, entropy becomes a concept that connects energy, information, and time. It is not only a measure of physical irreversibility but also of the amount of information needed to describe the world. Contemporary physics increasingly often treats information as one of the fundamental categories of for the description of reality – and entropy as its natural measure.

ENTROPY IN QUANTUM COMMUNICATION

Contemporary communication is increasingly quantum, and Shannon's information entropy has a quantum 'cousin' in von Neumann entropy, which allows us to assess not only how information-rich a quantum communication channel is, but also whether it is truly quantum in nature, and therefore secure, or whether it only pretends to be so and is vulnerable to classical attacks. Quantum entropies are useful in certifying the quantum nature of information channels, allowing, among other things, an assessment of whether the channel loses any essential information component related to quantum entanglement.

ENTROPY IN THE UNIVERSE

Entropy also plays an important role in many of our attempts to describe the evolution of the Universe. Not only does it determine the thermodynamic arrow of time but it also suggests the direction of processes from the hypothetical Big Bang to possible future scenarios. The early Universe was very dense and characterised by low entropy. Over time, entropy increases, matter and energy become increasingly dispersed, and the Universe becomes thermodynamically dead.

The fact that this reasoning is far from certain is demonstrated by the presence of black holes through which information seems to 'leak' somewhere (?) away from our Universe, as suggested by Bekenstein and Hawking, only to later return. The problem will remain unresolved at least until we finally manage to formulate a generally acceptable theory of quantum gravity, as well as the thermodynamics of quantum systems far from equilibrium.

Before Claude Shannon introduced a new measure of information to the scientific world and wanted to give it a catchy name, he visited the great John von Neumann, who advised him to call the new measure entropy, arguing that 'No one knows what entropy is anyway, and that gives you an advantage in any discussion'.

Today, as Jerzy Dajka argues, our knowledge is far more complete, and entropy has evolved from an intuitive idea used by early physicists into a well-established mathematical concept with properties documented by theorems. However, the concept of entropy is still sometimes misused by those who forget that even the most powerful theorems require certain assumptions to be fulfilled in order to be valid.