

**CONCEPTUAL RECONSTRUCTION OF THE ENTROPY PRINCIPLE IN MODERN PHYSICS A PHILOSOPHICAL AND HISTORICAL REVIEW**Zulfadhli<sup>1</sup>, Fatima Hassan<sup>2</sup>, Maria Bugeja<sup>3</sup>, and Marc Heinen<sup>4</sup><sup>1</sup> Bandung Institute of Technology, Bandung, Indonesia<sup>2</sup> Sudan University of Science and Technology, Khartoum, Sudan<sup>3</sup> Malta College of Arts, Science, and Technology, Paola, Malta<sup>4</sup> Luxembourg Institute of Science and Technology, Käerjeng, Luxembourg**Corresponding Author:**

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**Abstract**

This article reconstructs the conceptual principle of entropy in modern physics using a historical-critical approach that integrates the perspectives of classical thermodynamics, statistical physics, and modern cosmology. Entropy, originally introduced as a measure of irreversibility in thermodynamics, has evolved into a probabilistic concept that links the microscopic and macroscopic states of a system through statistical theory. This development has given rise to various formulations of entropy that influence how physicists understand order, the arrow of time, and the evolution of the cosmos. In statistical physics, entropy reflects the number of possible microstates, while in modern cosmology, horizon entropy and information entropy play a role in explaining the broader dynamics of the universe. Philosophical studies of entropy reveal profound implications for how we view the second law of thermodynamics, the status of laws of nature, and the relationship between the structure of physics and scientific epistemology. Through a critical review of recent literature in physics and the philosophy of science, this article shows that the meaning of entropy continues to evolve, reflecting an integration of theory, observation, and conceptual interpretation. The key findings demonstrate that entropy is not simply a technical measure, but a dynamic theoretical construct that shapes our understanding of the order and disorder of nature. This article enriches contemporary discourse in the philosophy of physics by emphasizing the importance of historical and reflective analysis of this fundamental scientific concept.

**Keywords:** Entropy, Philosophy of Physics, Thermodynamics

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## INTRODUCTION

Research into the concept of entropy in modern physics is crucial because it is one of the fundamental ideas shaping how humans understand the universe. Since its introduction in the context of classical thermodynamics, entropy has served not only as a physical quantity but also as an epistemological concept mediating the relationship between order, disorder, and change in nature (Bourgeois dkk, 2024). Subsequent developments have significantly expanded its meaning, extending beyond its technical function as a measure of the irreversibility of thermal processes. This shift raises profound philosophical questions about the nature of natural law, the direction of time, and the status of the objectivity of scientific knowledge. Therefore, a conceptual study of entropy cannot be separated from accompanying philosophical and historical reflection (De Assis dkk, 2024). This article begins with the realization that a narrow and ahistorical understanding of entropy has the potential to obscure the complexity of its scientific meaning. Therefore, this study aims to reconstruct a more comprehensive and reflective conceptual understanding of entropy.

The urgency of this research is also driven by the fact that the concept of entropy is often used across disciplines without adequate epistemological clarity. In philosophical discourse, cosmology, and even the social sciences, entropy is often understood metaphorically as a symbol of chaos or system degradation (Pekola & Karimi, 2024). This interpretation often ignores its rigorous physical foundations and complex conceptual history. Consequently, entropy has the potential to be misleading in both scientific and philosophical contexts. This research argues that conceptual clarification of entropy is an academic imperative to ensure its use remains within a valid scientific framework (Vom Ende & Malvetti, 2024). By tracing the evolution of entropy from classical thermodynamics to statistical physics and modern cosmology, this article seeks to demonstrate that entropy is a dynamic concept whose meaning is shaped by specific theoretical contexts. Therefore, this research is not merely descriptive but also critical of the implicit assumptions in the meaning of entropy.

Furthermore, developments in modern physics have shown that entropy can no longer be understood solely as a macroscopic quantity associated with heat engines. In statistical physics, entropy is reconstructed as a probabilistic measure of microscopic states, while in cosmology, entropy plays a crucial role in understanding the evolution of the universe and the direction of cosmic time (Shimada & Akatsuka, 2024). This expansion of the domain requires profound conceptual adjustments and serious philosophical reflection. Without historical and philosophical analysis, this shift in meaning risks being understood fragmentarily. Therefore, this study positions entropy as a meeting point between physics, philosophy, and the history of science. This approach allows for a more comprehensive analysis of the changing meaning of entropy and its implications for understanding the laws of nature. Thus, this article contributes to enriching the discourse on contemporary philosophy of physics.

Overall, this study aims to answer the fundamental question of how the concept of entropy evolved and what the philosophical implications of this evolution are. This question is relevant not only for physicists but also for philosophers of science interested in the structure and dynamics of scientific knowledge. By placing entropy in its historical context, this study seeks to demonstrate that scientific concepts are not static but rather evolve along with changing paradigms and theoretical frameworks. This approach emphasizes that scientific

understanding is always historical and conceptual. Therefore, this article is based on the belief that philosophical reflection on fundamental physical concepts is an integral part of the development of science. This research is expected to make a significant theoretical contribution to the study of the philosophy of physics and the history of science.

The classical literature on entropy is rooted in the development of 19th-century thermodynamics, particularly through the work of Rudolf Clausius and Lord Kelvin (Kruglov, 2024). Clausius introduced entropy as a quantity related to energy transformation and the irreversibility of thermal processes. Within this framework, entropy is understood as an increasing state function in a closed system, as formulated in the second law of thermodynamics. The classical literature emphasized the macroscopic aspects of entropy and its relationship to the efficiency of heat engines (Manoharan & Shaji, 2025). This approach was phenomenological, starting from empirical observations of thermal systems without direct reference to the microscopic structure of matter. Nevertheless, the classical concept of entropy has become the foundation for modern understanding of the direction of natural processes. This literature demonstrates that from its inception, entropy has contained a conceptual dimension that goes beyond mere technical calculations.

Subsequent developments in the literature on statistical physics, particularly through Ludwig Boltzmann, brought about a radical change in the meaning of entropy. Boltzmann reconstructed entropy as a measure of the number of microscopic states corresponding to a given macroscopic state (Lu dkk, 2025). This probabilistic approach links entropy to the concepts of chance and uncertainty, shifting the focus from phenomenological descriptions to mechanistic explanations. The literature on statistical physics emphasizes that the second law of thermodynamics is statistical, not absolute. This has given rise to philosophical debates about the status of natural laws and the role of probability in physics. Thus, this literature enriches the understanding of entropy while opening up space for epistemological reflection (D'Agostino & Luciano, 2024). This shift demonstrates that entropy is not simply a physical quantity, but also a theoretical concept rich in philosophical significance.

In the literature on modern physics and cosmology, entropy has acquired new, broader dimensions. The concept of entropy is used to explain the evolution of the universe, cosmic structure, and the direction of cosmological time (Maleki dkk, 2024). Research on gravitational entropy and black holes, for example, shows that entropy is not only relevant to conventional thermal systems. The cosmological literature extends the concept of entropy to a universal scale, raising profound questions about the origins of cosmic order. This approach challenges the classical understanding of entropy as a mere measure of disorder (Samuelson, 2025). Thus, the cosmological literature demonstrates both the conceptual flexibility of entropy and the complexity of its meaning. This study demonstrates that entropy continues to undergo reinterpretation as physical theory develops.

The literature on the philosophy of science provides a reflective framework for understanding these changing meanings of entropy (Dharma dkk, 2024). Philosophers of science highlight that the concept of entropy reflects the relationship between theory, observation, and conceptual interpretation. In this context, entropy is viewed as a theoretical construct dependent on certain methodological assumptions. The literature on the philosophy of physics also discusses the implications of entropy for the concepts of time, causality, and determinism. Thus, philosophical studies help uncover the normative and epistemological dimensions of entropy (Said & Sakr, 2023). This literature emphasizes that scientific understanding is inseparable from its underlying conceptual framework. Therefore, philosophical analysis is an important element in critically reconstructing the concept of entropy.

Several historical studies demonstrate that changes in the meaning of entropy do not occur linearly, but rather through debate and conceptual revision. The literature on the history of science highlights the role of social, technological, and methodological contexts in shaping the concept of entropy (Said & Sakr, 2025). This historical approach demonstrates that entropy evolves alongside changes in the paradigm of physics. Thus, the history of the concept of entropy reflects the internal dynamics of science. This literature emphasizes the importance of understanding entropy as a product of intellectual history, rather than as an ahistorical concept. Therefore, historical studies serve as a crucial foundation for this research.

Based on this literature review, it can be concluded that entropy is a multidimensional concept that cannot be reduced to a single definition. Classical, statistical, cosmological, and philosophical literature each provide complementary perspectives. However, there remains a gap in research that comprehensively integrates the historical and philosophical dimensions. This article seeks to fill this gap by presenting a comprehensive conceptual reconstruction of entropy. Thus, this literature review serves as a theoretical foundation for the analysis that will be developed in the following section.

## RESEARCH METHOD

This research uses a qualitative approach with a historical-critical literature review method. This approach was chosen because the research objective is to reconstruct the conceptual meaning of entropy, not to test empirical hypotheses. Literature review allows researchers to trace the development of ideas and concepts in depth through written sources. This method is relevant for the study of philosophy of physics, which emphasizes conceptual analysis and theoretical argumentation. Therefore, this research focuses on the interpretation and synthesis of relevant scientific literature. A qualitative approach allows for a richer and more reflective exploration of meaning. Therefore, this method is considered most appropriate for the research objectives.

Data sources for this research include classical and modern physics textbooks, reputable journal articles, and philosophy of science literature. Textbooks are used to understand the formal formulation and theoretical development of the concept of entropy. Journal articles provide cutting-edge discourse and contemporary debates regarding entropy. The philosophy of science literature provides an interpretive framework for the conceptual analysis. Sources were selected selectively, considering relevance and academic authority. Thus, the data used has high scientific credibility. This approach ensures that the analysis is based on reliable sources.

Data analysis was conducted through scientific hermeneutics, an interpretive approach to scientific texts. Hermeneutics was used to interpret the meaning of the concept of entropy within its historical and theoretical context. This approach allows for a deeper understanding of conceptual assumptions and implications. Furthermore, comparative conceptual analysis was used to compare various formulations of entropy. By comparing classical, statistical, and cosmological approaches, this study uncovered significant shifts in meaning. This method helped identify conceptual continuities and discontinuities.

The research steps included literature collection, source classification by period and theoretical approach, and interpretive analysis. Each source was analyzed to identify the definition, assumptions, and implications of the concept of entropy. The results of the analysis were then synthesized to construct a coherent historical and philosophical narrative. This process was carried out iteratively to ensure consistency of interpretation. Thus, this study produced a systematic conceptual reconstruction. This approach enabled a comprehensive understanding of the evolution of the concept of entropy.

The validity of the study was maintained through triangulation of sources and analytical approaches. By using various types of literature, this study reduced interpretive bias. Furthermore, philosophical reflection was conducted critically to avoid unfounded generalizations. This method ensured that the research results had a strong theoretical foundation. Thus, the methodological approach used consistently supports the research objectives.

## RESULTS AND DISCUSSION

Research results show that the concept of entropy in classical thermodynamics serves as a primary indicator of the irreversibility of natural processes. Within this framework, entropy is understood as a physical quantity that tends to always increase in a closed system, as formulated in the second law of thermodynamics (Herrera, 2024). The increase in entropy indicates that natural processes have a specific direction that cannot be spontaneously reversed, such as the transfer of heat from a high-temperature object to a low-temperature object. Thus, entropy becomes a parameter that distinguishes between processes that are possible and those that are impossible in nature. This understanding also confirms the existence of an "arrow of time" in macroscopic physics, where time is no longer symmetrical as in many equations of classical mechanics. Therefore, classical entropy provides a conceptual basis for the notion of order, energy degradation, and the tendency of systems to move toward a state of thermal equilibrium.

In statistical physics, the concept of entropy underwent a fundamental reconstruction with the introduction of a probabilistic interpretation of microscopic states. Through the contributions of scientists like Boltzmann and Gibbs, entropy is no longer understood solely as a macroscopic thermodynamic quantity, but rather as a measure of the number of microscopic configurations (microstates) consistent with a given macroscopic state (Gorska dkk, 2024). In this perspective, entropy is directly related to probability—the more possible particle configurations that can form a given state, the higher its entropy. Thus, the second law of thermodynamics is understood not as an absolute, deterministic law, but as a statistical law stating that systems tend to move toward the most probabilistically probable state. This shift fundamentally changes the meaning of entropy, from a phenomenological concept to one rooted in probability theory and particle mechanics.

The analysis shows that this statistical approach introduces a dimension of epistemological uncertainty into physics. While in classical thermodynamics irreversibility appears as an absolute inevitability, in statistical physics it is understood as a highly probable, but not entirely impossible, tendency to be violated at the microscopic scale (Rieger dkk, 2024). In other words, entropy is no longer completely deterministic, but rather probabilistic. This has profound philosophical implications for understanding the laws of nature: the laws of physics should not always be understood as absolute certainties, but rather as statements of very high probabilities. This shift opens up discussions about the relationship between objective reality and the limitations of human knowledge, and about the extent to which the laws of nature reflect the ontological structure of the world or are simply effective statistical models.

In the context of cosmology, entropy takes on a new, broader dimension. This concept is used to understand the evolution of the universe as a whole, including the origins of cosmic structure and the direction of cosmological time (Il'ich Kruglov, 2024). Cosmic entropy relates to the distribution of matter and energy on large scales, such as the formation of galaxies, stars, and black holes. The question of why the universe began in a state of low entropy has become a fundamental issue in modern cosmology. Thus, entropy is no longer limited to laboratory systems or heat engines but has become a key concept in explaining the history and future of

the universe. This approach significantly expands the domain of the concept of entropy, from the microscopic scale of particles to the macrocosmic scale of the universe's structure.

This research also found that in popular discourse, the concept of disorder is often misinterpreted as a direct synonym for entropy (Zhao dkk, 2024). However, in a scientific context, entropy is not synonymous with chaos per se, but rather relates to the number of possible configurations a system can occupy. A system can appear visually orderly, yet possess high entropy due to the large number of possible microscopic configurations. Therefore, simplifying entropy as "chaos" is potentially misleading and obscures its scientific meaning. This understanding requires more careful conceptual clarification so that the term entropy does not lose its theoretical precision when used outside the context of physics.

The research findings demonstrate continuity between the classical and modern concepts of entropy. Despite a shift in meaning from a phenomenological to a statistical interpretation, the fundamental principle of irreversibility remains the conceptual core. The second law of thermodynamics remains fundamental, although now understood within a probabilistic framework. This demonstrates that the development of the concept of entropy was not a complete discontinuity, but rather underwent a gradual transformation that enriched its meaning. This dynamic reflects how science advances through reinterpretation, not simply the replacement of old concepts with new ones.

Historical analysis reveals that changes in the concept of entropy were significantly influenced by methodological developments in physics (Sun & Ni, 2024). The emergence of statistical mechanics, atomic theory, and probabilistic mathematical methods played a significant role in reformulating entropy. Furthermore, the paradigm shift in physics—from classical mechanics to modern physics—allowed for the reinterpretation of fundamental concepts. Thus, entropy reflects the internal dynamics of science, where theories, methods, and conceptual frameworks influence each other. This conceptual evolution demonstrates that scientific understanding is not static but continually adapts as instruments and theoretical perspectives evolve.

The research findings also highlight the important role of philosophy in clarifying the meaning of entropy. Philosophical reflection helps uncover theoretical assumptions often hidden behind mathematical formulations, such as assumptions about time, probability, and microscopic reality (Fuchs dkk, 2024). The philosophy of physics provides space to question whether irreversibility is ontological or epistemological, and the relationship between statistical descriptions and the underlying physical reality. Thus, philosophy is not merely an external commentary on science but actively contributes to deepening and clarifying the scientific concept itself.

Overall, the research findings demonstrate that entropy is a concept that continues to evolve alongside the development of theories and methods in physics. This evolution reflects the dynamic relationship between theory, observation, interpretation, and philosophical reflection. From the steam engine to modern cosmology, entropy has undergone significant expansions in meaning without losing its conceptual core of irreversibility. Thus, entropy serves as a clear example of conceptual dynamics in physics and illustrates how science evolves through a continuous dialogue between empirical facts and the theoretical frameworks that interpret them.

This discussion confirms that the shift in the meaning of entropy from the framework of classical thermodynamics to modern statistical physics and cosmology has profound philosophical implications (Molina-Vilaplana dkk, 2024). Entropy is no longer simply understood as a technical parameter for measuring energy changes in physical systems, but also as a concept that shapes how we understand time, order, and the direction of change in nature. In this context, entropy plays a role in establishing what is known as the "direction of time" in physics, namely the idea that natural processes have an orientation from the past to the future, characterized by increasing entropy. This shows that entropy functions not only in the

operational realm but also has an ontological dimension, as it helps determine how physical reality is understood as something that develops irreversibly. Thus, entropy becomes part of the ontological framework of physics, connecting the structure of natural law with human temporal experience.

The conceptual shift in entropy also demonstrates the limitations of a reductionist approach in comprehensively explaining physical phenomena. While the reductionist view assumes all phenomena can be fully explained by deterministic microscopic laws, the statistical interpretation of entropy demonstrates that the relationship between the micro and macro levels is not that simple (Gorska dkk, 2024). Macroscopic entropy arises from the vast and diverse microscopic configurations, so its understanding requires an integration of descriptions of individual particles and their collective patterns. In other words, physical reality exhibits a complexity that cannot be reduced to a single level of analysis. This discussion confirms that an integrative approach—one that combines macro and micro perspectives—is more adequate for explaining the dynamics of physical systems. The complexity of physical reality is reflected in the fact that macroscopic laws have both relative autonomy and a deep connection with their microscopic basis.

This discussion also demonstrates that the second law of thermodynamics, long viewed as a universal and absolute law, actually has a contextual dimension within the statistical framework. In the probabilistic interpretation, the increase in entropy is not a logical inevitability that cannot be violated, but rather a highly probable tendency due to the dominance of high-probability states. This means that irreversibility is highly probable, but not impossible, for fluctuations on a specific scale. This challenges the classical deterministic view that views the laws of nature as absolute statements without exception. Consequently, the understanding of the laws of physics shifts from a model of absolute certainty to a probabilistic model that remains empirically robust but conceptually more open. This shift has profound implications for the philosophy of science, particularly in the debate about determinism and indeterminism in nature.

The cosmological implications of entropy open up a broader discourse on the origins and structure of the universe (Sadeghkhan, 2024). If entropy is always increasing, then a fundamental question arises: why did the universe begin in a state of very low entropy? Cosmic entropy is key to understanding the evolution of large structures such as galaxies and black holes, as well as to explaining the direction of cosmological time. The idea of a "heat death" of the universe as a consequence of increasing maximum entropy also raises philosophical reflections on the future of the cosmos. Cosmic entropy challenges intuitive understandings of initial order, as highly ordered initial conditions are precisely the prerequisites for the subsequent evolution of complexity. Thus, entropy is not only a physical concept but also a starting point for cosmological reflection on the meaning of the beginning and end of the universe.

Further philosophical discussions highlight the role of language and metaphor in the interpretation of entropy. In popular communication, entropy is often simplified as "chaos" or "disorder," even though these terms do not fully reflect its technical meaning in statistical physics. Metaphors help bridge scientific concepts with lay understanding, but metaphorical simplifications risk creating conceptual misunderstandings. For example, not all systems with high entropy appear visually chaotic, and not all order implies low entropy. Therefore, conceptual clarification is crucial to prevent the scientific meaning of entropy from being distorted by imprecise language. This reflection demonstrates that the philosophy of language and conceptual analysis play a significant role in maintaining the accuracy of scientific understanding.

Thus, this study demonstrates that conceptual reconstruction of entropy is necessary to maintain scientific coherence amidst the development of modern physical theory. A historical approach helps trace how the meaning of entropy changes with changing methodologies and paradigms, while a philosophical approach allows for a critical analysis of the assumptions underlying its interpretation. The integration of these two approaches makes a significant contribution to a more reflective and comprehensive understanding of modern physics. Entropy, in its evolving meaning, exemplifies how scientific concepts develop not only through experiments and mathematical equations, but also through a continuous conceptual dialogue between theory, observation, and philosophical reflection.

## CONCLUSION

This study concludes that the concept of entropy has undergone a significant evolution in meaning since its emergence within the framework of classical thermodynamics in the 19th century. Initially, entropy was understood as a macroscopic quantity related to the irreversibility and degradation of energy in a closed system. However, with the development of statistical mechanics and probability theory, its meaning was reconstructed as a measure of the number of possible microscopic configurations underlying a thermodynamic state. This shift was not merely technical but reflected a paradigm shift in physics—from a phenomenological approach to a more fundamental microscopic-statistical one. In the context of modern cosmology, entropy even acquired a new dimension related to the evolution of the universe as a whole. Thus, entropy cannot be understood ahistorically, as if its meaning were fixed and final from the beginning. Rather, it must be understood as a concept that evolves within the dynamics of the history of science, influenced by changes in theories, methods, and the horizons of scientific inquiry.

The conceptual reconstruction conducted in this study demonstrates that entropy has closely intertwined physical and philosophical dimensions. Physically, entropy is related to the second law of thermodynamics, the probabilistic structure of microscopic systems, and the direction of time in nature. However, philosophically, entropy raises fundamental questions about determinism, irreversibility, the ontological status of statistical laws, and the relationship between order and disorder. This concept lies at the intersection of mathematical description and metaphysical interpretation, and therefore cannot be reduced to either dimension alone. A comprehensive understanding of entropy requires the integration of a historical perspective—to examine how the concept developed—and a conceptual perspective—to analyze its underlying theoretical assumptions. Therefore, this study not only clarifies the technical aspects of entropy in physics but also enriches the discourse in the philosophy of physics by demonstrating how a single scientific concept can open up a broad scope for epistemological and ontological reflection.

Finally, this study emphasizes the importance of philosophical reflection in the development and maturation of physical concepts. Without such reflection, scientific concepts risk being understood narrowly, limited to their formal formulations, without recognizing their deeper conceptual implications. Entropy serves as a concrete example of how scientific concepts dynamically evolve through the interaction of theory, experimentation, mathematical interpretation, and philosophical debate. Its evolution demonstrates that science is not a static collection of facts, but rather a continuous process involving revision, reinterpretation, and expansion of meaning. Thus, this article is expected to not only contribute to the understanding of entropy in physics but also encourage a more intense dialogue between physics and the philosophy of science, so that both can enrich each other in an effort to understand the structure and dynamics of reality more deeply and sustainably.

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