An Intelligence Measure Based on Energy-Information Conversion

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Abstract

What is intelligence? This is one of the core problems in artificial intelligence, yet to date there is no universally accepted definition. From the perspective of the relationship between intelligence and life, this paper proposes that intelligence is a fundamental capability and characteristic attribute of living organisms—an ability to adapt to the environment and maintain existence through information processing by striving to achieve maximum information with minimal energy. Building upon this foundation, a novel viewpoint is presented that intelligence constitutes the mutual conversion capability between matter-energy and information. Furthermore, new concepts including measurement and calculation methods for intelligence, average intelligence, and comprehensive intelligence are introduced. Finally, the quantitative conversion relationships among matter, energy, and information are discussed, identifying the upper bound of intelligence and the lower bound of energy-to-information conversion. For the convenience of practical application, a dimensionless intelligence measurement formula is further provided, offering feasible computational methods for the quantitative analysis of intelligence levels in intelligent systems.

Full Text

An Intelligent Measure Based on Energy-Information Conversion

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Abstract

What is intelligence? This question stands as one of the core issues in artificial intelligence, yet no universally accepted definition exists. From the perspective of the relationship between intelligence and life, this paper proposes that intelligence is the fundamental capacity and characteristic attribute of living organisms—the ability to achieve maximum information with minimum energy expenditure, and to adapt to environments and maintain existence through information processing. Building upon this foundation, we present the novel viewpoint that intelligence is the conversion capability between material energy and information. We further introduce new concepts including intelligence measurement, average intelligence, and comprehensive intelligence. Finally, we discuss the quantitative conversion relationships among matter, energy, and information, identify the upper bound of intelligence and the lower bound of energy-to-information conversion, and provide a dimensionless calculation formula for intelligence measurement to facilitate practical application. This work offers a feasible computational method for the quantitative analysis of intelligence levels in intelligent systems.

Keywords: matter, relationship between energy and information, intelligence, intelligent measurement

1. Introduction

Undoubtedly, artificial intelligence represents one of today' s most prominent topics. However, what constitutes intelligence remains without a universally accepted definition. Some argue that thinking is intelligence, others that decision-making is intelligence, while still others claim that adaptive capacity or learning constitutes intelligence [**?**]. This phenomenon indicates that the essence of intelligence remains poorly understood.

Regarding intelligence, we must first understand natural and biological intelligence before addressing artificial intelligence. It is widely recognized that living organisms possess intelligence, with humans being the most intelligent species on Earth. The goal of artificial intelligence is to enable machines to exhibit intelligence comparable to humans. Therefore, to explore the essence of intelligence, we must first examine the underlying logic of biological intelligence and life systems: Why do living organisms possess intelligence? What is the value and significance of intelligence for life? Life systems are far-from-equilibrium, self-organizing, self-generating (replicating), self-adaptive living physical information systems with continuous evolutionary capabilities. Modern physics holds that matter and information are unified, and that the world consists of various physical information systems, yet life represents a unique existence.

As a special physical information system, the living organism follows two fundamental principles: (1) the principle of minimum free energy, and (2) the principle of maximum information.

The principle of minimum free energy states that when a system is in equilibrium, its free energy is minimized [?]. As an independent system with boundaries, a living organism maintains minimum free energy to preserve internal stability and balance within an unstable environment. The principle of maximum information states that as a self-organizing, self-replicating, and self-adaptive system, life selects for maximum information during self-mutation and evolution [?]. These two fundamental principles guide the stable existence and evolutionary direction of life systems from both energy and information perspectives, with the dual driving forces of maximizing information and minimizing energy jointly promoting the stable evolutionary development of living organisms.

2. The Essence of Intelligence

Throughout their lives, organisms constantly strive to acquire energy and information, utilizing these resources to maintain themselves and adapt to changing environments, thereby stabilizing their physical (energy) information systems and ensuring their continuation. Through billions of years of evolution, organisms have become the world's most successful energy-information transformation systems. This capacity to convert surrounding environmental material (energy) information into the energy and information needed for their own survival, process it internally, and then feed it back into the environment constitutes intelligence. Therefore, intelligence is the fundamental ability and characteristic attribute of living organisms—the capacity to achieve maximum information with minimum energy and to utilize information for environmental adaptation and existence maintenance. Information utilization encompasses processes such as information acquisition, memory, computation, and output [?].

Species occupying different ecological niches possess different levels of intelligence, and even within the same species, environmental and evolutionary differences can create variations in intelligence. To calculate and compare intelligence levels across organisms, it is necessary to further analyze the relationships among energy, information, and intelligence.

In summary, the conversion and transmission between energy and information constitute basic life functions, with intelligence directly related to the efficiency and effectiveness of energy and information processing. Since all activities—including energy and information acquisition, information computation and processing, physical movement, and information output—require energy consumption, organisms supply necessary energy for various activities through metabolic and circulatory biochemical processes that convert food and nutrients into chemical, electromagnetic, and thermal energy. This achieves dynamic energy balance while striving to minimize free energy. According to the law of energy conservation, the total energy remains unchanged before and after conversion by living organisms. Energy obtained from the environment is largely emitted back into nature as heat after absorption and utilization, with the total quantity unchanged, though its form may shift from chemical to electromagnetic, mechanical, thermal, or information energy. Conversion efficiency depends on organism structure and metabolic processes. For the same species, structural and metabolic principles are similar, resulting in minimal efficiency differences. Only the amount of free energy may vary with survival environments—for instance, polar bears in extreme cold require more free energy stored as fat compared to other bear species.

Thus, intelligence appears more closely related to information acquisition, processing, and manipulation. Through various sensory receptors, organisms can perceive environmental states and changes, identify and process information through sensory organs, learn and remember various phenomena, and make decisions for action. In the same environment, different species' abilities and efficiencies in processing and utilizing information directly affect their survival capabilities and ecological niches. In other words, intelligence level determines an animal' s survival capacity and position in the ecological chain. Humans, as Earth' s most intelligent species, have outcompeted all other animals and occupy the top of the ecological chain.

From a physical perspective, the living organism system represents a dynamic energy-information conversion system in nature. The meaning of life lies in applying converted energy and information back to the physical world to change and influence nature. The efficiency and effectiveness of information conversion and processing serve as key intelligence metrics, while information processing speed and energy consumption determine the efficiency and effectiveness of information processing.

Note that efficiency and effectiveness in information processing are distinct concepts: high efficiency means fast speed and short time; high effectiveness means low cost and minimal energy consumption. From an energy consumption perspective, sensory information acquisition, transmission, processing, and storage all require energy. The sum of all energy related to information constitutes the information conversion cost.

During brain evolution, following the principle of maximum information, brain capacity continuously increased, laying the material foundation for rapid information processing. To quickly process information similar to past experiences, the brain nervous system improves information processing efficiency and reduces energy consumption through memory and reuse of previous experiential information. Simultaneously, life evolution follows the principle of minimum free energy, requiring organisms to maintain balance between energy consumption and acquisition. Brain energy consumption must remain relatively balanced with the organism' s energy acquisition capacity—excessive brain capacity would impair survival capability, making the brain-body ratio a more reasonable metric than brain capacity alone.

DNA replication cannot occur without some errors. Replication errors causing mutations benefit population diversity but must not be excessive, as this could cause systemic collapse. M. Eigen established selection value theory in his hypercycle theory, demonstrating through experimental simulation and theoretical proof at the molecular level that life system evolution is a process of continuously optimizing selection value toward maximum information [?]. Similarly, the strength of information memorized in the brain nervous system decays over time, reducing memory accuracy. Memory errors hinder the utilization of past experiences but may benefit innovation by creating new thinking pathways. German psychologist Hermann Ebbinghaus discovered regular patterns in the brain nervous system and formulated the forgetting curve [?], shown in Figure 1 [Figure 1: see original paper]. This curve demonstrates that memory accuracy gradually decreases over time. To effectively utilize the brain' s information memory and processing capabilities and adapt to environmental changes, organisms must continuously acquire new information while repeatedly learning to maximize retention of valuable information and experiences. Consequently, life exhibits curiosity about novel things and preference for new information, while establishing a learning mechanism that integrates old and new information. Bayesian formulas represent one mathematical expression of such mechanisms.

Figure 1. Forgetting Curve Diagram [?]

3. Intelligence Measurement

Assume G is a living (intelligent) entity with intelligence W. As a conversion system between energy E and information I, the life entity G can be represented as a function of variables E and I. Disregarding life' s purposiveness, intelligence W is its capacity to acquire and utilize information—viewed from the energy-information relationship, this is the ability to convert environmental material-energy information into the organism and then back into the surrounding environment. This can be expressed as: $W = G(E, I)$, where E represents the energy consumed by the organism to acquire and process information, and I represents the information obtained, processed, and converted to the environment. Apart from outputting necessary energy and maintaining organic stability, the organism' s energy consumption is primarily used for information processing, including perception, memory, computation, and output.

Note: Here, I refers to new or effective information acquired by sensory receptors, as outdated and ineffective information holds no value for life, wastes resources and energy, and is what life systems actively avoid.

Assuming that within unit time t, an organism processes information amount I and consumes energy E, then W represents the capacity of organism G to acquire and process information per unit time. According to the principles of minimum free energy and maximum information, the less energy consumed and the greater the information processed, the higher the intelligence. Therefore, W is inversely proportional to E and directly proportional to I, yielding:

$$W = G(E, I) = \alpha \frac{I}{E}$$

where α relates to biological category, environment, and objectives, generally treated as a constant within the [0-1] interval during calculation. If time is considered, W can be regarded as the energy-information conversion capacity of G per unit time.

If we consider the sequential steps of energy-information processing—including input, computation, and output—then:

$$W = W_1 + W_2 + W_3$$

where W_1 represents input intelligence, W_2 represents computation/storage/processing intelligence, and W_3 represents output intelligence, corresponding to perceptual intelligence, decision-making/computational intelligence, and behavioral intelligence, respectively.

Substituting equation (1) into (2) yields the composite intelligence measure. The above calculation does not consider conversion efficiency. If we incorporate the time factor t for information processing, with varying information amounts processed during different time periods where E and I are functions of time t, we can calculate dynamic conversion efficiency. To compute intelligence over a specific time period from start time t_0 to end time t_1, the average intelligence equals the total intelligence divided by $T = t_1 - t_0$.

The average intelligence over period T is given by the time differential of function G with respect to E and I. For example, human intelligence may vary across different life stages from birth through primary school, from childhood to youth, or represent the average intelligence of an agent during time $T = t_1 - t_0$ while completing a specific task.

If we consider task completion as an important intelligence indicator, we can assign different weights to coefficient α based on completion degree—for instance, 0 or 0.1 for incomplete, 0.5 for half-complete, and 1.0 for complete.

4. The Relationship Among Matter, Energy, and Information

The natural world consists of matter, energy, and information, which are intertwined in their natural state. Matter contains energy and information, and matter can be converted into energy while energy can also be converted into matter. Natural information, as a representation of material motion states, cannot exist independently of matter. However, life can separate information from its material (energy) containment and utilize it. As part of nature, life is also composed of material (energy) information, but its organic structure is built upon the sequential relationships of material energy—information. Therefore, from its inception, life possesses the capacity to acquire and utilize information, namely intelligence. From the perspective of matter-energy-information relationships, life serves as a medium and manipulator for the mutual conversion between material energy and information.

Life relies on its unique sensory receptors and signal processing systems to extract environmental material-energy states and changes, thereby cognizing the world, and can utilize information and energy to transform and produce new material (energy), achieving conversion between material (energy) and information.

According to formula (1) W = α I/E, we have EW = α I. If we set $\alpha = 1$, then EW = I, allowing calculation of the conversion between energy E and information I, where W serves as the energy-information conversion factor.

In 2019, Melvin M. Vopson [?] established the equivalence relationship among matter, energy, and information, shown in Figure 2 [Figure 2: see original paper]. Based on Einstein' s mass-energy relation $E = MC^2$, matter and energy can be mutually converted. The energy-information relationship is given by mc^2 = k_b T ln(2), where T = 300K, C is the speed of light, k_b is the Boltzmann constant, and information is measured in bits, m in kilograms. Calculation shows that 1 bit of information corresponds to a mass of approximately 3.19$×10^{-38}$ kg.

Figure 2. Equivalence of Matter, Energy, and Information

Note: This data is based on the energy consumption required to erase or store 1 bit of information, not a direct energy-information conversion, which differs from the mass-energy conversion pathway.

According to the mass-energy conversion formula, the energy corresponding to 1 bit of information is calculated as: 3.19$×10^{-38}$ × (3$×10^{{10})}{2}$ / (300 ln(2)) = 2.871$×10^{-27}$ / 207.944 = 1.38$×10^{-29}$ Joules. This represents the lower bound of energy consumption per bit of information.

Since intelligence is information/energy, then:

$$\omega = \frac{1}{1.38 \times 10^{-29}} = 7.243 \times 10^{28} \text{ bit/J}$$

represents the upper bound of intelligence. From the energy-information conversion perspective, 7.243$×10^{28}$ constitutes the theoretical maximum limit of intelligence—the theoretical limit for single energy-information conversion. In reality, information as a representation of energy or material states and changes manifests in various forms such as heat, frequency, light, electricity, and magnetic fields. Acquiring different, changing spatiotemporal information in complex environments is far from simple. Although billions of years of evolution have produced diverse and complex forms of intelligence, natural living organisms' intelligence remains vastly distant from the theoretical limit.

To facilitate intelligence computation and application, we introduce the constant ω into formula (1) as the fundamental constant for matter-energy-information transformation:

$$W = \beta\alpha\frac{I}{E}, \quad \beta = \frac{1}{8 \times 7.243 \times 10^{28}} = 0.17258 \times 10^{-30} \text{ (J/Byte)}$$

where Byte represents bytes (1 Byte = 8 bits), J represents Joules (1 Joule = 1 Watt-second). After this conversion, intelligence becomes dimensionless:

$$W = 0.17258 \times 10^{-30}\alpha\frac{I}{E}$$

where I is information amount in bytes, E is energy in Joules, and W is dimensionless intelligence. Since β' s unit J/Byte cancels with Byte/J. Considering that 1.0$×10^{-30}$ is too minuscule for practical application as a universal constant, we omit this factor in actual intelligence calculations and use only the numerical value 0.17258 as the daily intelligence measurement formula:

$$W = 0.17258\alpha\frac{I}{E}$$

Note: Calculation using formula (5) yields a relative intelligence index without dimensions.

Although matter, energy, and information are physically closely related with certain equivalence relationships, mass and energy can be mutually converted through natural and artificial nuclear reactions, while no independent mutual conversion between energy and information has been discovered. Only through intelligent agents can information be separated from and converted with energy and matter. Intelligence is the conversion capability between material energy and information, dependent on the intelligent agent and representing its fundamental attribute. Intelligent agents must minimize free energy, maximize information amount, increase information processing efficiency and effectiveness, and continuously optimize their energy-information transformation from both efficiency and effectiveness perspectives.

5. Conclusion

Based on deep analysis of intelligence essence, this paper proposes the novel perspective that intelligence is the conversion capability between material energy and information. We further introduce new concepts including intelligence measurement methods, average intelligence, and comprehensive intelligence. Finally, we discuss quantitative conversion relationships between matter, energy, and information, identify the upper bound of intelligence and lower bound of energy consumption, and provide a dimensionless calculation formula for intelligence measurement.

Intelligence measurement can be used to evaluate and compare the intelligence levels of artificial intelligence systems. For instance, while current large language models have achieved tremendous success, they also consume enormous energy and resources. Although these models appear to surpass human intelligence in many domains, calculating their intelligence metrics reveals they remain far from human levels. Furthermore, intelligence measurement provides a feasible computational method for quantitative analysis of intelligence levels in intelligent systems, offering meaningful guidance for the improvement and development of artificial intelligence.

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Note: Figure translations are in progress. See original paper for figures.