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Research Article

General Definitions of Information, Intelligence, and Consciousness from the Perspective of Generalized Natural Computing

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Abstract

Atoms themselves have no thoughts and cannot be thinking. Why does the human body, which is composed of atoms, have consciousness? The widely used concepts of information and intelligence in today's science, which are related to this, do not yet have appropriate general definitions. Answering these interesting questions is a crucial issue for technological development in the historical context of human society entering the era of intelligence. The key lies in how to fully utilize the existing fundamental theories subtly related to information science. Here we attempt to give the definition of general information and general intelligence from the perspective of generalized natural computing, based on the least action principle, Hamilton-Jacobi equation, dynamic programming, reinforcement learning, and point out the relationship between the two. The least action principle for describing conservative systems can be seen as an intelligent manifestation of natural matter, and its equivalent form, the Hamilton-Jacobi equation, can be extended to describe quantum phenomena and is a special case of continuous dynamic programming equations. Dynamic programming is an efficient optimization method under deterministic models, while reinforcement learning, as a manifestation of biological intelligence, is its model-free version. The statement that reinforcement learning is the most promising machine learning method has a profound physical foundation. General information is defined as the degree to which a certain environmental element determines the behavior of the subject. General intelligence is defined as the automatic optimization ability of the action or value function of a system with a certain degree of conservatism. Intelligence is a basic property of material systems, rather than an emergent property that only complex systems possess. Consciousness is an advanced intelligent phenomenon, a reconstruction of quasi conservative systems based on complex systems.

Keywords

Consciousness, Intelligence, Information, Conservative Systems, Reinforcement Learning, Dynamic Programming

1. Introduction

Today's society is about to transition from an information society to an intelligent society. The social needs and scientific exploration make complexity science and artificial intelligence become the two major themes of today's science. The core problem of complex system is to explore the source of life and consciousness [1-4]. The purpose of artificial intel-

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ligence is to explore the essence of general intelligence (intelligence for short) [5-7] and obtain machines with certain intelligence that can realize part of human functions. However, the basic physical principles and the discussion of the essence of computing have not received enough attention in these two studies. This study will recognize the essence of intelligence and consciousness from the perspective of natural computing based on the least action principle and Hamilton-Jacobi equation, as well as give the definition of general information.

Computational thinking is the greatest scientific thought of the 20th century [8, 9], surpassing the shock, scope, and time scale brought by other major scientific theories. Computing is usually understood as numerical transformation under certain rules. We think that in the paradigm of computer science, computing can be defined as formal transformations or numerical transformations that can be described or controlled. The concept of computation has experienced a changing process from only people can calculate, to machines can calculate, and then to all things can calculate, here computing is a quantitative change or information transformation [10] of the interaction attributes of material systems. Understanding complex natural phenomena with computational thinking will strengthen our understanding of nature and computation.

The current artificial intelligence technology is based on special natural computing, which refers to the physical process that can be transformed into Turing computing. It can be divided into three types: (1) Computing inspired by nature, including artificial neural networks, evolutionary algorithms, swarm intelligence, artificial immune system, and reinforcement learning; (2) The synthesis of natural phenomena in computers, including fractal geometry, artificial life, membrane computing, cellular automata, etc; (3) Computing with natural materials, including DNA computing, quantum computing, etc [11]. These computing modes assist us in solving decision-making problems in complex systems or complex environments, as well as building new computing systems. Generalized natural computing refers to all physical processes that can extract information, including the motion of conservative systems, dissipative systems, or advanced complex systems. Next, we will explore information and intelligence from a conservative system perspective.

2. Methods

2.1. Physical Description of Conservative Systems

Conservative system is a kind of magic existence in nature. It has excellent and simple physical properties and cybernetics properties. It is not only a world without energy loss, but also an excellent optimal control system. But this situation is very rare for human daily life, and it usually occurs in two extreme situations: orbital mechanics and quantum mechanics. So we treat the weak dissipative system as conservative as possible. For a long time, physics and artificial intelligence have been relatively estranged from each other. Now, we hope to clarify the essence of intelligence from a fundamental scientific level by combining the cybernetic properties of conservative systems with the principles of reinforcement learning, and fundamentally promote the development of artificial intelligence.

For conservative systems, two equivalent descriptions in physics are the least action principle and Hamilton-Jacobi equation. Our basic points unfold from here. The Euler-Lagrange action S (1), is a scalar that characterizes the evolution of a conservative system, indicating the inherent evolution trend of such a physical system.

$$S(t_0, x_0, t, x) = \int_{t_0}^{t} L(x, u, s)\mathrm{d}s \tag{1}$$

Here t represents time, x represents spatial position, u represents the velocity of the particle, and L is the dynamic state function of a conservative system. The evolution of such a system results in the action S taking its minimum value. This amount of action is determined by the starting point and the endpoint, and the amount of action used by the observer represents the ultimate cause of the motion of the basic material system [12].

The Hamilton-Jacobi equation (2) is the only mechanical description that can express particle motion as waves, revealing the duality between trajectories and wavefronts [13]. This ability to describe reality in the form of waves is the core of physics, because the Schrödinger equation, as the basic equation of quantum mechanics, can be derived from Hamilton-Jacobi equation [14]. It can also be said that Hamilton-Jacobi equation is the classical limit form of Schrödinger equation.

$$\frac{\partial S}{\partial t} + H(x, \nabla S, t) = 0 \tag{2}$$

Here H represents the generalized energy of a conservative system. In the equation, S is called the Hamilton-Jacobi action, and its different values represent different equal phase wave surfaces, reflecting the wave nature of material motion. From the perspective of optimal control, S is the value function that determines the behavior of the system.

The Hamilton-Jacobi action S (x, t) (3) indicates that when a particle reaching (x, t) from an unknown initial position and initial velocity, natural computing provides a choice, thus minimizing it. The motion trajectory of particles is obtained from the solution S (x, t) of the Hamilton-Jacobi equation, indicating that the Hamilton-Jacobi action S (x, t) acts as a field guiding particle motion and seems to be the action used by Nature [12].

$$S(x, t) = \min_{x_0, u(s)} \{S_0(x_0) + \int_0^t L(x, u, s)\mathrm{d}s\} \tag{3}$$

The particle nature is reflected in the gradient of Hamilton-Jacobi action, i.e. $\nabla S = p$, which is the momentum of particle motion. The trajectory generated by this momentum is the trajectory of motion with the optimal value taken by the value function. This shows that wave-particle duality is not only possessed by microscopic particles, but also by general mechanical phenomena.

At the same time, we will also see that Hamilton-Jacobi equation is a simplified version of Hamilton-Jacobi-Bellman (HJB) equation (4) [15], which is the basic equation of continuous dynamic programming in optimal control. Dynamic programming refers to a type of optimization problem solving method that satisfies the principle of optimality or has no aftereffect, and its spiritual essence is information sufficiency or complete certainty.

2.2. Inspiration from Reinforcement Learning and Dynamic Programmming

The three major schools of artificial intelligence have the following understanding of the concept of intelligence. Intelligence in Symbolism is an optimization algorithm designed by computer to simulate biological intelligence and the laws of nature. Intelligence in Connectionism is the ability to quickly find a satisfactory solution in a huge search space. Intelligence in Behaviorism is an individual's adaptive ability to the environment.

Reinforcement learning is the most prominent method of behaviorism, and also the most potential basic machine learning paradigm. It has been successfully applied to games, shopping software, and some mechanical movement learning, but there are no major successful industrial application cases and universal adoption. The difficulty of its industrial application lies in the formalization difficulty of complex environments, and the difficulty of defining rewards. However, reinforcement learning has become a hot academic topic at present. Its charms or advantages lie in its origin in the general laws of animal and human intelligent behavior, its highly simple definition of intelligent behavior, its close connection with dynamic programming, and its successful application in simple systems. Reinforcement learning can be seen as the origin of intelligence in the biological sense.

The original meaning of reinforcement learning is to improve the behavior strategy by analyzing the reward and return expectation brought by various behaviors, so as to maximize the value of state-behavior. Its common idea with dynamic programming is to maximize the value of the decision-making process. The difference is that one is a model-free algorithm characterized by environmental interaction, and the other is a model-based optimization algorithm [16]. Reinforcement learning can be understood as the approximation algorithm of dynamic programming in which the environmental state loses its information sufficiency, that is, it can only be partially observed.

Dynamic programming is a limiting case of reinforcement learning in which the environmental state is fully observed by the agent and the state value function meets the optimality principle, which is embodied in Bellman equation in discrete systems and HJB equation (4) in continuous systems. The Bellman equation [16] can also be viewed as a numerical solution for solving HJB partial differential equations.

$$V_t(t,x) + \min_u \{g(x,u) + V_x(t,x) f(x,u)\} = 0 \tag{4}$$

Here x represents the state variable of the environment, u is the control variable, V(t,x) represents the performance indicator function of the decision-making process, g (x, u) represents the cost incurred in the case of state x and control u, f (x, u) describes the rule of environmental state change, which is equal to the rate of change of state variable x over time t. An important physical connotation of the HJB equation is that, under the principle of optimality, the total effect of the influencing factors of the value function over time keeps the value function unchanged. However, the HJB equation is a variant of the Hamilton-Jacobi equation, which arises when there are dynamic constraints that affect the system speed. The Hamilton-Jacobi equation is a partial differential equation that gives a complete description of the dynamics of a system in terms of the action function S. The difference in form between the HJB equation and the Hamilton-Jacobi equation lies in the presence of control variables. The fundamental difference in content lies in the essential difference between the physical system described by the two. The former describes a complex multivariable dissipative system, while the latter describes a simple conservative system. The Hamilton-Jacobi equation is a necessary condition describing extremal geometry in generalizations of problems from the calculus of variations, and is a special case of the HJB equation. The HJB equation is a partial differential equation which is central to optimal control theory. The solution of the HJB equation is the value function which gives the minimum cost for a given dynamical system with an associated cost function.

3. Results and Discussion

3.1. Intelligence Nature of Conservative Systems and Intellegence Definition

From the introduction of conservative system, dynamic programming and reinforcement learning, we can see that Hamilton-Jacobi equation describing conservative system is a special case of HJB equation of continuous dynamic programming, and dynamic programming can also be regarded as a special case of reinforcement learning. Therefore, the automatic optimization property of conservative systems can be understood as intelligent properties, and they have the highest level of intelligent properties because their optimization ability is the highest. Conservative systems are considered dynamic systems with information conservation. The so-called conservation of information in physics refers to the complete determinacy of the evolution of physical states.

Here, intelligence can be defined as the optimization speed of system action or effective value function. The closer a system is to a conservative system, the higher its level of intelligence. That is to say, quantum systems and orbital mechanics systems are the most intelligent systems, while complex systems decrease in intelligence as their decision-making systems deviate from conservative systems. There are various definitions of intelligence available, but it can be roughly summarized as the ability to adapt to the environment, achieve goals, or be a form of profitability [17], which does not conflict with the definition of intelligence here.

Furthermore, all systems have intelligent properties. The wider the range of system response to the outside world, the faster and more accurate the stress speed, and the higher the level of intelligence. The more complex and advanced a system, the lower its intelligence level due to the frustrations or friction losses. At the same time, the essence of the intelligent process of advanced systems is to construct response mechanisms that approach conservative systems, such as human learning, sports training, etc. The generation of complex organic systems is based on their intelligent properties, manifested as the automatic optimization ability of integrated structures under external stress.

3.2. Intelligence and Consciousness

Intelligence is a concept in computer science that expresses the optimization ability of a system; Consciousness is a psychological concept that expresses one's awareness of the outside world and oneself, as well as the resulting behavioral decision-making mechanisms. Consciousness is divided into two essential dimensions, namely the subjective ego and the objective ego, or global availability and self-monitoring [18]. The subjective ego, also known as consciousness, the executor of psychological function, adjusts ego behavior according to the immediate environment to achieve optimal value. Another expression is global availability, which refers to a core area of the system that can be processed by information transmitted from other parts to generate globally available information that affects the entire system. This is consistent with the main viewpoint of the Global Workplace Theory [19-21], which is that the living system has a unique area for information sharing for all, thereby achieving individualization, and supported by experiments. The objective ego, also known as self-awareness, can recognize oneself and has a memory assist system. It establishes a value system in a relatively broad spatiotemporal area, guides attention, and completes target tasks in order based on causal relationships to achieve the optimal overall value. Our concept of intelligence is equivalent to the concept of subjective ego, as well as the concept of consciousness (or mentality) in panpsychism. The concept of intelligence tends to express the optimization ability of the system, while consciousness tends to express the integration ability of the value elements of the system. Based on the concept of this study, it is speculated that the core of biological consciousness is a quasi conservative system with sufficient information for optimal decision-making. It practically comes to the point of the integrated information theory [22], which states that the physical substrate of consciousness must be a maximum of intrinsic cause-effect power. In the process of interaction between individuals and the environment, it manifests as insufficient information, due to the dissipative nature of this interaction. As the complexity of the system increases, the information sufficiency gradually decreases, that is, the randomness of system behavior gradually increases, accompanied by a decrease in the intelligence level of the system. The evolution at the system level is not truly upgraded by intelligence, but by the value function generated by emerging elements.

Levine's explanatory gap [23] on consciousness, that is, the physical interpretation hard problem of consciousness, can be obviated due to the introduction of the automatic optimization property of the material system. The significant difference between physical processes and human consciousness lies in the significant differences in the constituent elements of their value functions that determines the behavior of a system. The former is based on simple physical fields, while the latter is based on diverse survival factors that maintain the operation of complex advanced systems. However, the optimization properties of the core area of the human brain are consistent with those of simple physical systems. The phenomena of abstraction, reasoning, imagination, and intuition in human thinking can be understood as different types of construction process of automatic optimization systems in complex interest environments.

The current progress in cognitive neuroscience indicates that human self-awareness is based on a paralimbic network located in the middle of the brain [24-26]. This region has two important physical characteristics, one is the presence of various forms of oscillations, and the other is the high energy consumption required to maintain oscillations. The waves generated by oscillations have the property of a conservative field, which is completely decisive as reflected in the Huygens principle [27], and thus it can be called a quasi conservative system. And high energy consumption is the physical condition for maintaining a state of oscillation and self-awareness, which is consistent with the clinical experience of life [25, 26]. This is the physical basis for the generation of consciousness and self-awareness.

The generation of self-awareness or objective ego is the central theme of consciousness or psychology research. The definition of intelligence here can provide ideas for this problem. The state of human consciousness can be switched between the subject ego and the object ego at will. Subjective ego state is manifested as sleep state, extreme sport, and the flow state of the heart during work, which is also the active state or intelligent state that reinforcement learning in artificial intelligence attempts to achieve. The object ego is based on the memory system to bring myself into the value calculation system, grasp the change rules of things based on reinforcement learning, and adjust my own behavior to achieve the optimization of the overall interests.

3.3. The Perspective of Information and Computation

Next, we will understand the motion properties of conservative systems from the perspectives of information and computation. Information theory, originating from C.E. Shannon, has become a cognitive approach and a universal language in many disciplines. Shannon information is a measure of the probability of the occurrence of a symbol sequence, or defined as the magnitude of eliminating uncertainty [28, 29]. That is, the smaller the probability of an event occurring, the greater the uncertainty, and the greater the amount of information it brings. It is mainly used in the fields of statistics and communication. Later, a generalized definition of information was the response or interpretation caused by one system to stimuli from another system [30]. These all contribute to obtaining a more accurate general definition of information.

At the level of physical mechanics, there is still a lack of clear definitions of information, but two things are confirmed: firstly, information is a binary relationship, that is, interaction; secondly, information is the degree of conservatism, that is, the degree of decisiveness, rather than the strength of the force. Specifically, information expresses the degree to which one thing determines the motion state of another, and the amount of information expresses a measure of this degree of determination, which can be taken between 0 and 1. If a thing is completely unaffected by the signal of another thing, its information content is zero. If the state transformation of a thing is completely determined by another thing, then the maximum value of information is taken as 1, which is known as sufficient information. In physics, information can be understood as the proportion of the force exerted by an object on another object in its resultant force. More specifically, information is the proportion of the component of the force exerted by an object on another object in its resultant force direction to its resultant force. For conservative systems or other deterministic systems with complete certainty, they are considered information conserved or information sufficient. The degree to which the system deviates from a conservative system means the degree of inadequacy of the information involved in the interaction. Shannon information, which is applicable to specific fields, expresses that the smaller the probability of similar events occurring, the greater the amount of information generated, indicating that this effect has a greater degree of decisiveness on the system. These laid the physical foundation to establish a general definition of information.

Therefore, general information is defined as the degree to which a certain environmental element determines the behavior of the subject. For general organisms or higher level individuals, information is the decisive degree of the utility attributes or benefit attributes of environmental factors on individual survival. Information is essentially a cybernetic state quantity that expresses the mutual influence between things. And intelligence is a process property of optimization in which things interact with each other. Thus, we can see that both information and intelligence are properties of interactions, one is a state quantity, and the other is a process quantity. More precisely, information is an intensity quantity, not a extensive quantity. Therefore, there is no concept of the total amount of information in a system. The usual amount of information in communication theory refers to the quantity or scale of a certain type of information source.

The invention of electronic computers in the 20th century has had a profound impact on various fields of today's society. The computational ideas behind them have led to major paradigm shift in engineering technology, mathematical computing, basic philosophy, and other fields. Computing has gradually become a mainstream research method, making computational theory the most important component of today's science. Computation refers to the numerical changes under certain rules, and the establishment of these rules is based on real-world computing applications and pure logical models. Computation can be divided into two categories: artificial computing, which is human designed computing, and generalized natural computing, which is the movement of natural matter.

In artificial computing, digital (or discrete) computing is the main pattern; in general natural computing, analog (or continuous) computing is the main pattern. The advantages of digital computing are accuracy, controllability, and versatility, while the disadvantages are low fault tolerance, consuming a large amount of underlying hardware resources, and high energy consumption. The current mainstream artificial intelligence methods based on this have not achieved high-level intelligence [31] and lack true learning ability [32]. The advantages and disadvantages of analog computing happen to be the reversal of the advantages and disadvantages of digital computing. In addition, analog computing has two special advantages: its relatively efficient automatic optimization ability and its ability to facilitate the integration of computing and storage [33-35]. For conservative systems, their motion can be understood as an efficient and automatically optimized analog computing, which belongs to a generalized natural computing and is of course a non-Turing computing. It's cybernetic property of efficient optimization has become a natural choice for intelligence. Therefore, quasi conservative system computing is a fascinating trend in the development of AI algorithms.

4. Conclusions

In the cognitive context of generalized natural computing, information, and intelligence, the definition of general intelligence is given from the Hamilton-Jacobi equation describing conservative systems and the relationship between dynamic programming equations and reinforcement learning. General intelligence is the automatic optimization ability of the system's value function, and general information is also defined as the degree to which a certain environmental element determines the behavior of the subject. Combining the latest research on consciousness in neuroscience, it is determined that human consciousness arises from a quasi conservative system, which is also a special intelligent phenomenon based on complex systems. Therefore, a unified attribute, namely the optimization ability of conservative systems, can be used to connect the biological and non biological worlds. It can be boldly predicted that all animal bodies have a region similar to the paralimbic network of the human brain, and all individual material systems have regions similar to conservative systems.

The definition of intelligence here is to provide an idea for the research of general artificial intelligence, which is to establish a decision-making system that is close to a conservative system to achieve efficient optimization capabilities. Currently, most artificial intelligence research is still focused on data-driven statistical modeling and learning. However, building a quasi conservative system with the strongest automatic optimization capability provides a good way to change this research paradigm. The general and physical definitions of information provide an important reference for establishing general information theory.

The intelligent evaluation of machine systems has become one of the important tasks in current artificial intelligence research, and there is still no effective evaluation method. According to our definition of intelligence, the automatic optimization ability of machine systems can be used as the main indicator of intelligence level, and its specific implementation needs further verification. One important issue that needs to be addressed is how intelligent representations such as abstraction, reasoning, imagination, and intuition can be reduced to an optimization ability.

This paper supports the long-standing panpsychism that intelligence or consciousness is a intrinsic nature of matter, rather than a emergent attribute based on simple material elements. It should be emphasized here that consciousness is not an independent existence of matter, nor is it a nonexistence, but rather a cybernetics property of matter systems about their interactions, or intelligence property. It is the third fundamental property of a matter system, in addition to the force charge properties (such as mass) and the energy properties (such as kinetic energy).

Abbreviations

HJB Hamilton-Jacobi-Bellman

Author Contributions

Linsen Zhang is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

Linsen Zhang is an associate professor of Wuhan Textile University. He obtained his PhD from the Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences in 2005, with a research focus on bioinformatics. He graduated from the postdoctoral research station in physics at Hunan Normal University in 2011, with a research focus on gravity theory. He visited the School of Mathematics at Sichuan University from September 2018 to June 2019, with a research focus on the theory and applications of partial differential equations. His current research work is dedicated to exploring the essence of information and intelligence, utilizing fundamental principles of physics and quantum physics.

Research Field

Linsen Zhang: bioinformatics, gravitational theory, mathematical methods in physics, information and intelligence