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RESEARCH ARTICLE

ZHONG Yi-xin

An investigation on theory of information-knowledge-intelligence transforms

Abstract It is recognized throughout history that understanding the properties of resources and transforming these resources into products are regarded as the nucleus of science and technology. Understanding the properties of information and transforming the information into products will then play a crucial role in the development of science and technology in the information age. An attempt is thus made in this paper to present the results on the concepts of information and the fundamental features of information transforms. Here information theory will be given a much broader scope than the well-known Shannon theory and the knowledge theory will go beyond the existing knowledge engineering. It is discovered in the paper that the transformations from information to knowledge and further to intelligence constitute the core mechanism of intelligence formation and is hence named the mechanism approach to intelligence research. It is also discovered that the major approaches to artificial intelligence in history, the structuralism, functionalism and behaviorism, can harmoniously be unified within the framework of the mechanism approach and no longer be contradictory.

Keywords comprehensive information theory, knowledge theory, unified theory of artificial intelligence, information-knowledge-intelligence transforms

1 Introduction

Historical phenomena are very often repeated in some way. The current status of the research on artificial intelligence, for example, is experiencing a kind of repetition of the story of "The Blind Men and the Elephant" – different approaches from different viewpoints create different explanations on intelligence.

It is well know that there have been three major approaches to the research in artificial intelligence: first is the structuralism-based neural network approach, which began in 1943; second is the functionalism-based expert system approach, which began in 1956; and third is the behaviorism-based sensor-motor approach, which started in 1990. All of these have been successful in making progresses in certain respects, but have remained independent from each other with very rare cooperation. What is worse is that there have been several disagreements between each other: Minsky and Papert published a book in 1969 criticizing the neural network approach as having "no scientific meaning" while the neural network researchers fought back in 1987 with the slogan "AI is dead, long live neural networks". In 1990, Brooks demonstrated a walking robot and a crawler simulator to show that artificial intelligence can be produced without knowledge representation and reasoning (criticizing the expert system approach).

These disagreements show that all three approaches failed to catch the real essence of the "AI elephant". Whether AI should be a structure simulator of the human brain, or a function simulator of intelligent systems, or a behavior simulator of intelligent beings? There is no agreement. We therefore need a better approach that would be able to capture the deeper meaning of intelligence, instead of merely in the form of structure, function and behavior.

Based on his own investigations, the author of this paper discovered that the most essential issue in AI research should be the mechanism of intelligence formation that is generally implemented by the information-knowledge-intelligence transformations. This has been called the mechanism approach to AI.

For a clear explanation of the essence of AI, some basic definitions related to AI research are given in Sect. 2, followed by the introductions to comprehensive information

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ZHONG Yi-xin (✉)
School of Information Engineering, Beijing University of Posts and Telecommunications,
Beijing 100876, China
E-mail: zyx@bupt.edu.cn

theory in Sect. 3 and knowledge theory in Sect. 4. The unified AI theory is presented in Sect. 5 and some conclusions and remarks are made in Sect. 6.

2 Definition of intelligence and the related concepts [1]

Many definitions of intelligence exist nowadays. For example, the Webster English dictionary defines intelligence as "the capacity for understanding and other forms of adaptive behavior", while the Oxford English dictionary defines intelligence as "the power of seeing, learning, understanding, and knowing", and so on.

These definitions from the dictionaries are all right for everyday use. The definitions, however, are all superficial and phenomenal descriptions of intelligence that fail to touch its essence and therefore are not sufficient for science and technology.

Intelligence in most cases can generally be defined as the ability to understand and solve a problem. While it is completely correct, however, this definition needs to be clarified in depth.

As a matter of fact, intelligence should be a kind of purposive behavior. In other words, it would be impossible to have intelligence in any sense without purpose. On the other hand, general purpose may have a number of specific goals as its milestones in various stages. All specific goals are necessary steps for the implementation of the general purpose. Only when one has a clear purpose in mind, can he clearly discover and properly define the problem that should be dealt with and find the strategy to solve the problem. Therefore, it should be reasonable to define intelligence as "an ability to define the problem, to set the goal, and to find the proper strategy for solving the problem and reaching the goal towards the general purpose when facing a specific environment".

The next point one should consider is how to find the strategy to effectively solve the problem and reach the goal when the problem, the environment and the specific goal are given. This needs the ability to obtain the information concerning the problem, the environment, and the goal defined above, and the ability to refine the information into knowledge, and produce the strategy for solving the problem based on the information and knowledge directed by the goal.

Thus, a definition of intelligence can be stated as below:

Definition 1 Driven by the general purpose and constrained by a given environment, intelligence is the ability to define a problem that should be handled, to prescribe the goal for solving the problem, to acquire information about the problem, the environment and the goal, to refine the information into knowledge, to produce a strategy for the problem solving based on the related knowledge and directed by the goal, and to converse the strategy into action through which the problem at hand can efficiently be solved, the constraints from the environment can satisfactorily be met and the prescribed goal can successfully be reached.

The definition can also be expressed as below in Eq. (1).

$$\text{Intel (Info, } K, S, \text{ Exe} \mid \text{GP, } E; P, \text{ PG)} \tag{1}$$

where the symbols in Eq. (1), Intel, Info, K, S, Exe, GP, E, P and PG stand respectively for intelligence, information, knowledge, strategy, strategy execution, general purpose, environment, problem, and the prescribed goal.

It is seen from Eq. (1) that intelligence as a whole can relatively be divided into two parts that are mutually interrelated: implicit intelligence (the part after the vertical bar in Eq. (1)), and explicit intelligence (the part before the vertical bar in Eq. (1)).

Implicit intelligence refers to the ability to define the problem and define the goal for solving the problem in any given environment guided by the general purpose of the system, while the explicit intelligence refers to the ability to acquire the information concerning the problem, the environment and the goal defined by the implicit intelligence. The explicit intelligence also refers to the ability to produce the knowledge through the process of refining the information, and the ability to create the strategy for solving the problem through the use of the knowledge, the information and the goal. It is clear that implicit intelligence expresses the purpose of the intelligent system and explicit intelligence reflects the means for implementing the purpose.

The intelligence function shown in Eq. (1) is a complete process from problem definition to problem solving and hence is regarded as intelligence in the complete sense, whereas the process of producing knowledge and strategy creation is simply intelligence in the narrower sense. In any case, strategy is the major embodiment of intelligence and thus often termed the intelligent strategy. It is also clear that intelligence in the complete sense covers, and is supported by the entire process of human activities, while intelligence in the narrower sense covers only the activities within the human brain. It is important to know that intelligence in the narrower sense is just a part of intelligence in the complete sense and cannot exist independently.

The definition expressed in Eq. (1) is meaningful as it not only explains what intelligence is but also show how intelligence is produced and why intelligence is related with goal, information and knowledge. The intelligence described in Eq. (1) can be regarded as a model of human intelligence.

What is artificial intelligence then? Artificial intelligence is a similar term of machine intelligence of all kinds. Its definition can then be stated as below:

Definition 2 Artificial intelligence, AI in brief, is the ability, owned by the machine, to acquire information, to produce knowledge, to create strategy and make the corresponding action for solving the problem, meeting the constraints and reaching the goal when the problem, its environment and the goal for problem solving are given. It can also be expressed symbolically as:

$$\text{AI (Info, K, S, Exe} \mid \text{E, P, G)} \tag{2}$$

The symbols in Eq. (2), E, P, and G, are the preconditions

given by the user.

It can easily be seen by comparing Eq. (1) and Eq. (2) that there are distinct similarities as well as radical differences between AI and human intelligence. The similarity between them lies in the fact that both AI and human beings are intelligent systems. Their difference lies in the fact that human beings possess both implicit and explicit intelligence and AI can only have explicit intelligence. This is because humans generally have their purpose and goals whereas the goals of a machine can only be defined by the system designers. This difference determines that AI can only be an intelligent assistant to humans and cannot surpass human in general.

It is clearly shown from Eq. (1) and Eq. (2) that the ability to acquire information needed, the ability to produce knowledge related, and the ability to create strategy for solving a problem, are the crucial factors to both AI and human intelligence.

3 Comprehensive information theory [2]

Information is the source of intelligence. However, the theory of information accepted till the present is "The Mathematical Theory of Communication" established by Claude Shannon in 1948. Shannon's theory of information is almost perfect in communication engineering, but in the fields of intelligence research it is insufficient. This is because of the fact that only the form factor (waveform) is considered and the other factors like the content and the value of information are ignored in communication. In the field of intelligence research, for making an intelligent decision, all the three factors of information, that is, form, content, and value, must be carefully considered. Hence, a new theory of information is needed for meeting the needs of intelligence research.

The most fundamental definitions of information include the following.

Definition 3 Ontological information of any event is the event's self-description on its states at which the event may stay and is staying and the manner through which the states may vary.

Definition 4 Epistemological information a subject possesses concerning an event is the description, given by the subject, on the form, meaning and value about the states at which the event may stay and is staying and the manner through which the states may vary from one state to another. The form aspect is termed the syntactic information, the meaning aspect the semantic information, the value aspect the pragmatic information and the entirety of the three the comprehensive information.

The theory based on these definitions is called comprehensive information theory or CI theory in brief. The detailed discussion on comprehensive information theory can be found in Ref. [2] in which it is proved that the measure of the amount of Shannon information is a special case of that of CI as is shown in Fig. 1.

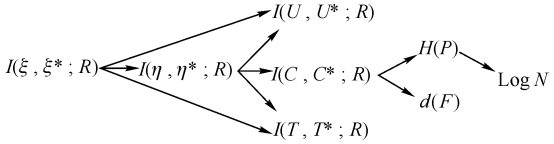

Fig. 1 Relationship of CI and Shannon information measures

The symbols in Fig. 1, $I(\xi, \xi^*; R)$, $I(\eta, \eta^*; R)$, $I(C, C^*; R)$, $I(T, T^*; R)$, $I(U, U^*; R)$ are respectively the formulas for integrated pragmatic information (CI), integrated semantic information, syntactic information, semantic information, and pragmatic information, and $H(P)$, $d(F)$, Log N are respectively the formulas for Shannon entropy, DeLuca-Termini entropy, and Boltzmann-Ashby entropy. The arrows in the figure mean that the one before the arrow can be reduced to the one after the arrow. The conditions associated with each of the reductions can be found in Ref. [2]. It is clearly seen from the figure that Shannon information is a special case of CI.

The importance of comprehensive information theory to intelligence research can be explained in the following way. The syntactic information can be used for the understanding of the formal aspect of an event, the semantic information can be used for understanding the content of the event, and the pragmatic information can be used for understanding the value of the event. Only by understanding the form, content, and value of an event, can one make an intelligent decision towards the event.

4 Knowledge theory [3]

It has been determined that, in most cases, the product of information processing will be knowledge instead of intelligence. The process of producing knowledge is a kind of general refining and thus may not involve specific purpose or objective. However, the process of intelligent strategy, or intelligence in the narrow sense, should have a clear purpose or specific goal.

What is knowledge then?

Definition 5 Knowledge is the nucleus of successful experience and may result from experience if the latter is positively verified. On the other hand, the experience before being verified is regarded only as empirical knowledge.

This definition is both correct and important, but a more descriptive one is needed.

Definition 6 Knowledge concerning a class of events is the description on the form, meaning and value about the states at which the event may stay and is staying and the law through which the states may vary from one state to another. The form aspect is termed the formal knowledge, the meaning aspect the content knowledge, the value aspect the value knowledge and the entirety of the three is termed the knowledge in the complete sense.

Comparing Definitions 4 and 6, it can be found that the major difference between them is "law" and "knowledge" in Definition 6 while it is "manner" and "epistemological

information" in Definition 4. This implies that knowledge can be summarized from (epistemological) information as "law" can be summarized from specific "manners".

It is rather evident from the discussions above that the fundamental methodology for producing knowledge from information is a process of inductive abstraction. In other words, the information concerning the states/manner, which is specific, shallow and individual in nature, may be refined into knowledge concerning the states/law, which is abstract, deep and general in nature, via the process of induction including such methods like association, analog, prediction, and interpolation, etc.

Based on the understanding about the definitions of information and knowledge obtained above, the relationship between information and knowledge can further be expressed in Fig. 2 below.

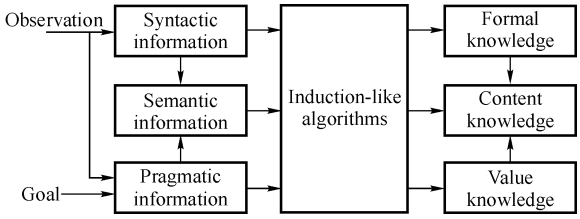

Fig. 2 Relation between information and knowledge

It can be seen from Fig. 2 that syntactic information can be acquired via observation and pragmatic information via calculation between syntactic information and the goal of the system, while semantic information can be acquired via integration and inference of syntactic and pragmatic information. Similarly, formal knowledge, value knowledge and content knowledge can respectively be obtained through induction-like algorithms associated with necessary calculation and deduction. The detailed algorithms related to the processes can be found in Ref. [3].

Another important concept in this regard is commonsense knowledge.

Definition 7 Commonsense knowledge is the regular knowledge that has been so popularized that it can be accepted by common people with no necessity of proof.

The interrelationships among the empirical knowledge, regular knowledge, and commonsense knowledge are shown in Fig. 3 in which empirical knowledge can be grown into regular knowledge if it is positively verified and regular knowledge may be grown into commonsense knowledge if it is popularized.

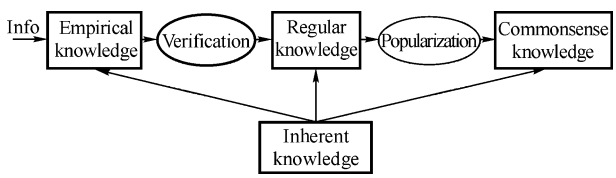

Fig. 3 Ecology of knowledge growth

It is also shown in Fig. 3 that the three categories of knowledge that can be learned and accumulated in practice are all supported by inherent knowledge that did not result from learning and teaching, but from previous generations via the process of evolution.

All in all, knowledge as an entirety is neither a static system, nor a closed system. Instead, it is a dynamic, open and growing system forming an ecological system, all deeply rooted in inherent knowledge.

In addition to the theory of knowledge growth and generation, knowledge theory has another part, the theory of knowledge transformation to intelligence, which is sometimes called the theory of knowledge activation. We introduce it in the next section.

5 Unified theory of artificial intelligence [4]

As mentioned previously, the activation of knowledge into intelligent strategy must have a specific given problem, clear constraints to problem solving, and the prescribed goal. Otherwise, the strategy activated from a general knowledge without specific problem-constraints-goal may not be useful. On the other hand, in accordance with the different kinds of knowledge and problem, the approaches for knowledge activation would also be different.

For regular knowledge, the process of its transformation into intelligence can be described as follows: given a problem in its original state, a set of constraints and a prescribed goal, a piece of knowledge from the knowledge base will be employed and applied to the problem and then a new state of the problem will be produced. Measure the distance between the new state of the problem and the prescribed goal and see whether the distance is decreasing or increasing. In the former case (distance decreasing), the strategy adopted can be regarded as effective. It is possible to find a strategy meeting both the objective constraints and the subjective goal. The process for producing a good strategy is dynamic and evolutionary in nature as is shown in Fig. 4 below.

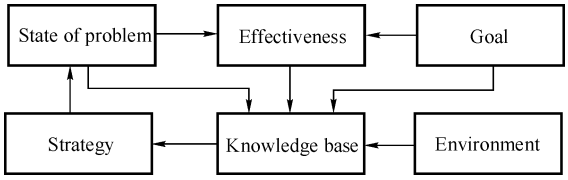

Fig. 4 Activation algorithm for regular knowledge

It is clearly seen from Fig. 4 that the process of creating an intelligent strategy is a mapping of regular knowledge into intelligence, whose embodiment is the intelligent strategy, guided by the prescribed goal and under the constraints given by the environment. This is completely the same mechanism as that in Expert Systems. For empirical knowledge, there is usually no regular knowledge base available and therefore cannot use the reasoning technology.

Instead, the intelligent strategy in this case is created through some kind of supervised training/learning process under the constraints and supported by inherent knowledge as is shown in Fig. 5.

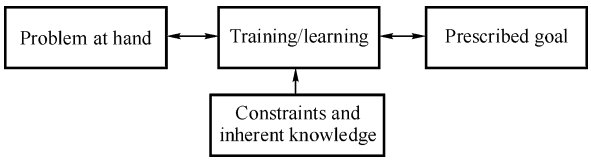

Fig. 5 Activation model for empirical knowledge

It is evident that the mechanism for activating empirical knowledge into intelligent strategy is the same as that in artificial neural networks.

For commonsense knowledge, the strategy can immediately be activated as long as the input pattern is recognized without the necessity of knowledge representation (like neural networks) and inference (like expert systems). This is typically the mechanism for a senor-motor system.

It is clear from the discussions above that the three approaches (structuralism-based neural networks, functionalism-based expert systems, and behaviorism-based sensor-motor systems) form a complementary and harmonious unification. All of the three have the same type of mechanism – the transformation of knowledge to intelligence. The only difference lies in the different category of knowledge. If the category of empirical knowledge is available, the activation process can naturally be implemented via neural networks. If regular knowledge is available, the activation process can then be implemented via expert systems. And if commonsense knowledge is available, the activation process can well be implemented via sensor-motor systems. Therefore, the existing approaches, the structuralism approach, the functionalism approach, and the behaviorism approach, have well been unified within the framework of the mechanism approach. The three approaches are no longer contradictory as they were over the past decades.

6 Impacts and open problems

In conclusion, two discoveries of significance are summarized here.

First, the transformations converting information to knowledge and further to intelligence constitute the core mechanism of intelligence formation of any kind in principle. Therefore, whenever a practical problem-constraints-goal is given, the task is to obtain the necessary information about the problem-constraints-goal, and then find the proper transformations for converting the information to knowledge and further to the intelligent strategy (the embodiment of intelligence) that can solve the problem, meet the constraints and reach the goal. According to the specific category of knowledge available, the corresponding systems mentioned above can respectively be employed. This mechanism approach to intelligence research may have great potential.

Second, the three approaches to AI, the structuralism approach, the functionalism approach, and the behaviorism approach in literature, can all be harmoniously unified within the framework of the mechanism approach. This may end the history of the three approaches being contradictory and possibly open a new stage in AI research.

On the other hand, however, there are many new problems that remain unsolved. Due to the limitation in space, only a few are mentioned here.

First, although the transformation from information to knowledge can in principle be implemented through various kinds of induction-like algorithms and the transformation from knowledge to intelligence can in principle be implemented through a deduction-like algorithm, the mathematical theory we have today may not be sufficient. This is due mainly to the uncertainty in the problem to be solved and the environment to be faced. Probability theory, fuzzy sets theory, and rough sets theory can handle some types of the uncertainty but they may be insufficient in more complex cases.

Second, there has been a lack of mathematical means to represent and process the semantic factor of information. Yet, semantic factor is unavoidably needed in intelligence research and therefore new visions and new mathematical theories are necessary.

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