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RESEARCH ARTICLE

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Advanced intelligence and mechanism approach

Abstract Advanced intelligence will feature the intelligence research in next 50 years. An understanding of the concept of advanced intelligence as well as its importance will be provided first, and detailed analysis on an approach, the mechanism approach, suitable to the advanced intelligence research will then be followed. And the mutual relationship among mechanism approach, traditional approaches existed in artificial intelligence research, and the cognitive informatics will be discussed. It is interesting to discover that mechanism approach is a good one to the Advanced Intelligence research and a unified form of the existed approaches to artificial intelligence.

Keywords natural intelligence, artificial intelligence, advanced intelligence, mechanism approach

1 Introduction

Human intelligence, or the ability of thinking, has long been a mystery in scientific research and has attracted many talents devoting themselves in the exploration in history. In the early days, psychologists and philosophers were the major forces in the studies. And then more and more scientists in natural science joined in. One group of the natural scientists is interested in understanding the secrets of human intelligence and another is in simulation of it in various ways. The former is termed the natural intelligence study and the latter the artificial intelligence research in wide sense.

It was believed in scientific circle in the past that structure, function, and behavior are the three windows from which one can look into the secrets of a system, and the structure of a system is the most fundamental one among the three. Therefore, simulating human intelligence through the way of mimicking the structure of human brain became most promising. The approach of structural simulation was gradually formed after the logical model of neuron published by McCulloch and Pitts in 1943 [1] and many results have been achieved since then [2–4].

It was realized later that the complexity related to human neural network may be a limit that the structural simulation approach cannot reach as the biological neural network contains more than 10^{10} neurons and each of the neuron may have as many as 10^3 connections to other neurons. If the complexity of the artificial neural network is reduced to an order that modern industry can achieve, the performance in intelligence of the system may drastically be degraded. This is a very bad dilemma.

New approaches to the simulation of human intelligence that can avoid the dilemma have thus been sought. Artificial intelligence was born at Dartmouth, Massachusetts, US in 1956 when a group of scientists got together for exploring the secrets of human intelligence through the way of function, instead of structure, simulation of the human intelligence by means of software for computer. This approach looked very well at the early stage of its development. Logic theorist, general problem solver, means and ends analysis, etc., one after another came out as its achievements [5–7].

It was recognized later that it is much too ambitious to deal with the problems solving in general. Therefore, much more efforts made to solve the problems in special domain, and the expert systems became the mainstream in function simulation. Variety of expert systems appeared during the period of 1970s [8]. It is not long, however, knowledge bottleneck was found a serious obstacle in the process of expert systems designing—the ability in acquisition, representation, and inference of knowledge needed are severely limited and are not easily overcome in a certain period of time.

To avoid both the difficulty of complexity dilemma in structure simulation and that of knowledge bottleneck in function simulation, the third research group grew up in early 1990s and that is the research aiming at the simulation of behavior of intelligent beings by using the methodology of "black box". It is believed that what is needed in artificial intelligence is to simulate the behavior of intelligent systems—take the right actions in response to the given conditions, that is the stimuli—responses relationship of intelligent system, or the so-called sensor-motor systems [9,10].

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It is clear that behavior simulation approach can avoid the difficulties encountered in both structure simulation and function simulation whereas this success leads to another problem—the sensor-motor systems can only satisfactorily simulate the relatively simple behaviors of intelligent systems. In other words, the behavior simulation approach can only deal with the intelligence in shallow level rather than with that in deeper level. This is also a severe limitation.

After all, the three approaches—the structure simulation approach, the function simulation approach, and the behavior simulation approach—have made impressive progresses during the past decades. On the other hand, however, each of them also faces critical difficulties which are not easy to overcome in near future.

It is noted that there have been a number of novel books published in the field of artificial intelligence in recent years. The book titled with *Artificial Intelligence: A New Synthesis* by Nilsson [11] and the one titled *Artificial Intelligence: A Modern Approach* by Russell et al. [12] are the representatives. Both the books have the feature that all the materials have been organized in the line of agent evolution, from the simple one (sensor-motor system) to the advanced one (neural network and expert system). It seemed that there is lack of the essential links among the three simulation approaches in both the books and they have been just simply put together in a straightforward way. In other words, there seems no progress with respect to the approaches to artificial intelligence research up to the present time.

2 Why is advanced intelligence considered?

On August 1–3, 2006, an International Conference on Artificial Intelligence was held in Beijing, China for celebrating the 50th anniversary of artificial intelligence. More than two hundred delegates from five continents (Asia, America, Africa, Europe and the Ocean) got together for summarizing the experiences achieved in the past decades in Artificial intelligence research, not only related to the function simulation approach but also to the other two approaches. At the same time, the problems confronted with all the three approaches were also reviewed. One of the common understandings reached from the conference is that, based on the summarization of the past experience as well as problems, a new stage of artificial intelligence research should be emphasized for another 50 years and the new stage of the research could be suggested to be named as advanced intelligence. Both the terminologies of artificial intelligence and advanced intelligence can interestingly be briefed as AI—showing the link between the two while the one facing in the future and the other experienced in the past.

Although it is hard to precisely define the domain of advanced intelligence for the time being, the following features may serve as good marks for it.

1) Both the natural intelligence and artificial intelligence are closely interrelated in advanced intelligence, instead of separate from each other like what it was in the past.

2) The significant frontiers in natural and artificial intelligence should receive much more attentions in the research on advanced intelligence, in addition to the elementary issues.

If taking the view of agent issues as Nilsson and Russell and others did recently, the advanced intelligence research may also be defined as topics closely related to the human intelligence and the advanced agents and the intelligence in human society or the agent society. This, of course, does not mean that all the other issues are no longer important. As a matter of fact, many issues related to the simple agent may better be solved when they are concerned with more aspects of the information related and more constraints from the real environment.

Because of the fact that the three major approaches, the structure simulation approach, the function simulation approach, and the behavior simulation approach, have all been confronting with critical problems as mentioned above, it is absolutely necessary to make efforts for finding a new, and better, approach to the research in the next stage. On the other hand, because of the fact that the new stage of the research, i.e. the advanced intelligence research, has been stood in front of researchers, the new approach to the advanced intelligence research is reasonably demanded.

3 Mechanism approach to advanced intelligence

For meeting the requirements from advanced intelligence research, the approaches currently used would not be sufficient. A new, and hence better, approach to advanced intelligence would thus be requested. From the point of view of methodology, a better candidate for approach to the research on an intelligent system, like humans, should be the one that can directly concentrate on the mechanism of intelligence formation. This is because of the fact that all the secrets related to the intelligence can be made clear only through the understanding of the mechanism of intelligence formation and no more. This can be named the mechanism approach to intelligence formation.

Intelligence is a sort of phenomenon that is well pervasively existed in the real world of living beings. Human intelligence is nevertheless the most powerful and typical sample for advanced intelligence. It would thus be reasonable to take human intelligence as an example in this study. To begin with, a general description for the entire process of human intelligence formation is necessarily given as a basic background of the discussions that will be carried out later in this paper. According to the current knowledge, human intelligence formation process consists of the following six steps in logic order.

Step 1 When facing a problem in real world, humans should be able to set up a prescribed goal in the brain for itself

to deal with the problem in later stage. Note that how a person can set up the prescribed goal properly is another theme (the implicit intelligence) that is a more complicated problem and needs to intensively study not in this paper but in the future.

Step 2 The sensing organs are then asked by the brain to acquire the information concerning the problem and the environment that will exert constraints to the process in dealing with the problem. This is the process of information acquisition. The information concerning the problem and the constraints, both from the real world, is often termed the original information.

Step 3 When all the needed information has been obtained already, that are named the acquired information, and they should be passed, via nerve system, to the brain for processing, analyzing and utilizing. This is the process of information transferring.

Step 4 When all the acquired information is sufficiently available, the brain will have to refine them into the related knowledge. This is the process of Cognition and its output is knowledge.

Step 5 If the information and the knowledge related to the goal, the problem and the constraints are available already the brain should have to produce the strategy for the problem solving. This is the process of Decision-making and its output is strategy.

Step 6 The strategy will then be passed, also via nerve system, to the actuators where the strategy will be conversed into the corresponding action through which the problem will be solved if all the steps mentioned above are all right. This is the process of execution of the strategy. If the problem is not solved satisfactorily, the error incurred in meeting the prescribed goal will serve as newly occurred information and the loop from Steps 1–6 will be restarted again till the problem is solved satisfactorily.

It is noted that the strategy is the embodiment of intelligence and often referred as intelligence in narrow sense whereas the ability embedded in the entire process from Steps 1–6 is referred the intelligence in completed sense.

The process analyzed above also shows how the intelligence in narrower sense is formed from the related knowledge and information. It is evident from the process that the core mechanism of human intelligence formation can be implemented through a series of transformations that will be discussed below.

For the conciseness of the paper, however, only the crucial parts (the core) of the series of the transformations that can converse the original information into sensed one, and then to knowledge and further to strategy in the process of intelligence formation, will be discussed in the section of this paper whereas the other parts of the transformations will have to be omitted yet without the loss of the generality.

Transform 1 From original information to acquired information

The first function for an intelligent system to perform is to get the information directly related to the problem P to be handled under given constraints C and the prescribed goal G. The information on G will be stored internally within the system while the information on P and C will have to be acquired from the outside world where the problem is presented. This is thus a conversion from original information, denoted by I_{O}, to the sensed information, denoted by I_E

$$T_1 : I_{\mathrm{O}} \mapsto I_E \tag{1}$$

The definitions on I_{O} and I_E in Eq. (1) are given below respectively.

Definition 1 Original information of an event in real world is defined as the event's self-description about the states at which the event may stay and the manner with which the state of the event may vary [13].

Note that the original information, I_{O}, is the purely objective facts about the event itself, the states and the manner, without subjective factors interfered and thus is really original source of information.

Definition 2 Acquired information of an event is a description, given by the subject, describing the states at which the event may stay and the manner with which the state may vary. As the subject has abilities for sensing, understanding and having goal in mind, the description on the state and the manner should be concerned with the form, meaning and utility with respect to the goal and are respectively called the form information, the meaning information, and the utility information while the trinity of the three is named the comprehensive information [13].

The transformation, T_1 shown in Eq. (1), which transforms the original information to the acquired information, may be implemented through different systems depending on which the component of sensed information is required. If, for instance, only form information is required, a specified kind of sensing system is then a good choice. If, on the other hand, however, the comprehensive information, including all the three components, is required at the same time, the sensing system combined with a proper knowledge base and a certain kind of logic algorithm will be needed. This can better be shown in Fig. 1.

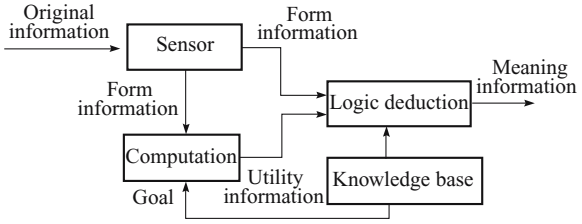

Fig. 1 Transformation conversing original information to acquired information

Figure 1 shows that the form information can be obtained from the output of a related sensing system and the utility information can be derived via the computation based on the comparison between the form information with the goal

stored in knowledge bases while the meaning information can then be produced via a logic deduction based on both form and utility information. For more detailed explanation, see Ref. [13]. After all, Eq. (1) can well be implemented in principle.

Transform 2 From information to knowledge

The transformation 2 converses the acquired information to knowledge. The basic concepts related to the transformation can be given below.

Definition 3 Knowledge concerning a certain category of events is the description, made by subjects, on the states at which the events may stay and the law with which the states may vary. As the subjects have abilities to sense the form, to understand the meaning, and to measure the value, the description should also include the three components: the form of the states and law observed that is called the formal knowledge, the meaning of the states and law understood that is named the content knowledge, and value of the states and law with respect to the subject's goal that is termed value knowledge. All the three aspects of the description constitute an entirety of knowledge [14].

The comparison of the Definitions 2 with 3 indicates that the crucial difference between the two definitions lies on the two key words: the manner in information and the law in knowledge. As a matter of fact, the law of state varying can generally be abstracted from the related manners of state varying. Thus, the transformation from acquired information to knowledge can be implemented through the inductive-like algorithms as expressed below

$$K \Leftarrow \bigcap \{I_E\} \tag{2}$$

where $\bigcap$ stands for a class of inductive operators; $\{I_E\}$ the sample set of the acquired information whereas K the knowledge produced from $\{I_E\}$. In some complicated cases, there may need a number of iterations between induction and deduction. The deduction itself can be expressed as

$$K_{\text{new}} \Leftarrow \Re\{K_{\text{old}}, C\} \tag{3}$$

where $\Re$ represents the deduction operator, K_{old} the knowledge already knew before deduction while K_{new} theknowledge newly deduced from K_{old} and C stands for the constraints that the deduction must follow.

More specifically, the formal knowledge can be refined from form information and value knowledge from utility information whereas content knowledge from meaning information through induction/deduction as indicated below

$$K_{\text{F}} \Leftarrow \bigcap \{I_{\text{sy}}\} \tag{4}$$

$$K_{\text{V}} \Leftarrow \bigcap \{I_{\text{pr}}\} \tag{5}$$

$$K_{\text{C}} \Leftarrow \bigcap \{\Re(K_{\text{F}}, K_{\text{V}}, I_{\text{sem}}, C)\} \tag{6}$$

where K_{F}, K_{C} and K_{V} respectively stand for the formal, the content and the value knowledge while I_{sy}, I_{sem} and I_{pr} for form, meaning and utility information. The detailed description on general algorithms related to Eqs. (4)–(6) can be referred to Ref. [14].

It is noted that the theme of data mining and knowledge discovery, very hot topics in literature these days, is in principle a special case of the transformation from form information to formal knowledge. Considering that most algorithms presented in data mining and knowledge discovery are statistics in nature, they may be assigned in the category of the algorithms expressed in Eq. (4). For example, a well-known mining algorithm for association rules between sets of items in a large database in Ref. [18] is a typical inductive algorithm of this kind.

In addition to the discussions mentioned above, it is also important to note a fundamental aspect of knowledge theory, the ecological properties of knowledge, which has been ignored in almost all literatures till the present time. In accordance with the different degrees of maturity in the process of its growth, knowledge can be classified into three categories: the empirical knowledge (the lower level of the degree of maturity), the regular knowledge (the standard level of the degree of maturity) and the common sense knowledge (the over matured level of the degree of maturity). All the three categories of knowledge are rooted from the instinctive, or inherent, knowledge. The corresponding definitions needed here are given as follows.

Definition 4 Empirical knowledge: the knowledge produced by induction leaning yet without positive verification is termed the empirical knowledge denoted by K_E. It may also be called the potential knowledge.

Definition 5 Regular knowledge: the regular knowledge, K_{R}, can be defined as matured knowledge. It is the second stage of knowledge growth. The empirical knowledge may grow into regular knowledge if it was positively verified through a certain scientific means.

Definition 6 Commonsense knowledge: common-sense knowledge, K_{CS}, is such part of regular knowledge that has been over matured and well popularized. Learning and reasoning processes are not needed in this case.

The relationship among the different categories of knowledge can be explicated in Fig. 2.

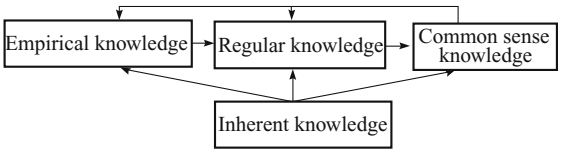

Fig. 2 Ecological link of knowledge

It is seen from Fig. 2 that inherent knowledge is the root from which the empirical, regular, and the common-sense knowledge can grow up one step after another with different degrees of maturity. On the other hand, the common-sense knowledge also serves as bases for the growth of empirical

and regular knowledge. It is well known that the inherent knowledge is the congenital one resulted from the long-term biological evolution whereas the empirical, the regular and the common-sense knowledge are acquired through the process of training and learning, but not innate.

Transform 3 From knowledge to intelligence in narrow sense (intelligent strategy)

The major task for decision-making is not as simple as to make a choice from a set of alternatives as was described in many books, but to create an intelligent strategy guided by the prescribed goal and based on the related knowledge and information. The so-produced strategy itself can be regarded as an intelligent guideline, or intelligent procedure, for the system to follow for problem solving successfully.

Definition 7 Strategy: an intelligent strategy for solving a problem is a sort of procedure or guideline along which the given problem could be satisfactorily solved, meeting the constraints and reaching the prescribed goal.

The transformation from the related knowledge and the specific information to the intelligent strategy, directed by the prescribed goal, can generally be expressed as

$$T_3 : (P, C, G; K) \mapsto S \tag{7}$$

The symbol T_3 denotes the transformational map, P the problem to be handled, C the constraints set up by the given environment, G the prescribed goal for problem solving, K the knowledge related to the problem solving and S the space of strategies.

Theoretically speaking, for any reasonably given P, C, G and K, there must exist a group of strategies such that the problem can be solved satisfactorily and among the strategies there may be at least a one leading to the optimal solution. The specific implementation of the transform will be dependent, of course, on the properties of the problem given, the constraints, the goal prescribed, and the knowledge possessed, particularly on the type of acceptable strategy as stated in the following.

If there is information related to P, C and G but no sufficient regular knowledge available and empirically intelligent strategy is acceptable, the empirical knowledge will be sufficient and Eq. (7) can then be established via learning, training, testing and revision approaches. As has been well known in literature, the discipline of artificial neural network [3,4] is proper means for this purpose.

When regular knowledge is available and regularly intelligent strategy is demanded, the regular knowledge must be fully used in this case and Eq. (7) could be implemented via a series of logic reasoning based on regular knowledge stored in knowledge bases. Obviously, this is the well-known approach of intelligent strategy formation called expert system [7,8], or traditional AI sometimes. It may be necessary to mention that a well-known discipline, the knowledge engineering proposed by Feigenbaum et al. in the 1970s for dealing with the issues of knowledge reasoning in expert systems, is a typical example of the implementation of Eq. (7) of this kind. However, Eq. (7) may have more forms for implementation as logic theory develops.

Whenever stereotyped intelligent strategy is concerned, the common-sense knowledge, including the instinctive knowledge and popular knowledge, will be used and Eq. (7) could be implemented by directly linking the input patterns and the corresponding output actions. As long as the specific input pattern is recognized the related output strategic action can directly be determined with no reasoning needed. This is the typical feature of intelligent strategy formation in the category of sensor-motor systems [9,10].

Up to this point, all the processes in core transformations, conversing information to knowledge and further to intelligence, have been described in brief in the section. It is clear that all the related algorithms needed for implementing the transformations are in principle feasible.

Clearly, the units of information cognition and decision-making are two consecutive inner cores of the intelligent system: the former transforms the acquired information into knowledge and the latter transforms the knowledge, combining with the related information and the goal, into the intelligent strategy. Both of them are non-linear transforms in nature and cannot be implemented merely by pure mathematical expressions.

In summary, the transforms briefly discussed in Sect. 3 do form the core mechanism of intelligence formation in general cases. What should be kept in mind is that it is the synergetic collaboration among all the transformations, expressed in Eqs. (1) to (7), which makes it possible for a system to have intelligence to a certain extent. This is the core mechanism approach to AI research.

4 Conclusions

It is recognized that comparing with the structure, function as well as behavior of any intelligent systems, mechanism of intelligence formation is much more essential to the understanding of intelligence and an approach directly attacking the mechanism of intelligence formation, which is the mechanism approach, should be of much more significance than the others.

Even more interestingly, as was discussed in Section 3, the neural networks (an embodiment of structure simulation approach), the expert systems (an embodiment of function simulation approach), and the sensor-motor systems (an embodiment of behavior simulation approach) are three special cases of mechanism approach under different and complementary conditions. In other words, the three approaches to artificial intelligence research existed so far could be harmoniously unified within the framework of the mechanism approach.

It is clear that the mechanism approach, which is implemented through the transform that converse information to knowledge and further to intelligence, or expressed in the

form of "information-knowledge-intelligence transform", can be regarded as the general approach to intelligence research while the structure simulation, function simulation, and behavior simulation regarded as special approaches. It is believed that the mechanism approach presented in the paper will play an important role in the research on Advanced Intelligence in the coming years.

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