On the Problem of Computability of Bounded Rationality Cognitive Solutions

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Let's not argue—let's do the math.
J. L. Lagrange

Abstract Modern science has not made the world less mysterious, and future discoveries may be even more surprising than the conclusions of relativity or quantum mechanics, confirming the thesis of A. Clarke that "advanced technology is indistinguishable from magic". In other words, with a certain level of technology development, an adequate understanding of them may require intellectual resources that exceed the capabilities of a single human, primarily for handling large amounts of information. What is it, how are cognitive processes defined and physically implemented in nature, how effectively can their technical simulation be implemented, and, finally, whether it is possible to build not just a supercomputer, but a superbrain for solving super tasks. These issues are currently at the forefront of current research in both natural and human sciences, as well as computer technology. In this chapter, the problem is considered in the aspect of finding solutions of "bounded rationality" that is, based on the regularization of solutions obtained using computable functions that are defined on a set of data taking into account certain specific or even personal cognitive biases.

Keywords Technology development · Artificial intelligence · Machine learning · Exo-intelligence · Cognitive functions

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1 Introduction

Formally considered a problem is that the cognitive processes occurring in the human brain, being a part of objective reality,[1, 2] do not obey the common logic-mathematical principles of modern physics. To describe cognitive processes we need new models and applied methods that, on the one hand, would meet the principle of physical explanation of the phenomenon of intelligence, and with another—would consider their "informational entity" that in quantum physics, for example, connected with the effect of "retro-causality", that is, the impact on the current state of the quantum object not only of past events but also events not yet held the future with the explanation of the phenomenon of quantum nonlocality or predictive modeling (calculations). The model that is constructive from the point of view of computer science should reflect aspects that are common to any type cognitive processes, related to their internal system, or more precisely, information organization, and not only with the properties of physical substance, which is a particular case can be considered as a carrier of cognitive processes.

Based on this, the research is based on the correspondence principle, which assumes that the formal description tools used at the system level reflect the properties of the studied objects that are available for measurement or experimental observation.[3, 4] According to this principle, the well-known properties of macroscopic physical substances in a 4-dimensional space–time continuum are characterized by the Archimedean metric and are accurately described by the properties of the real number field, but on the microscopic scale, the interaction processes of quantum particles have different nature and, therefore, are represented by operators in Hilbert space.

First of all, we will highlight the systemic essence of cognitive processes and try to understand by what kind of mathematical methods these processes can be adequately modeled, for example, to create artificial intelligence that combines the cognitive resources of people and classical Turing' machines in a common global exo-intelligent digital space.

The research attempts to provide answers to the questions formulated above, based on the modern paradigm of computer science, the metaphorical formulation of which follows the ideas of R. Descartes, namely "compute ergo sum" (I calculate, so I exist). The implementation of this paradigm applied to the engineering education system allows preventing the situation when a hypothetical global failure of all computer systems no one will be able to spend vital for civilization calculations in manual, not because it is beyond human possibilities, but because this skill has ceased to learn, and as a result, the knowledge in the Sciences become incomplete and simplified to the extent that their use only to control "magical" devices, not having a full description and understanding of the principles of their work.

Solving this problem on the way to creating hybrid human–machine exo-intelligent systems will allow the designs a new space of digital knowledge that exists not only in a verbal-declarative but also in an operational-computational form available both for people and machines.

In our studies, we based a number of theses, namely: Thesis 1: intelligence as a phenomenon subject to natural physical laws; Thesis 2: the principle of "presumption of neutrality", namely the need to find "natural" explanations for all the peculiarities of the manifestation of intelligence via formally defined cognitive functions; Thesis 3: the nature of intelligence is related to the organization of information connections between memory resources and data perception, and not to the properties of the substance in which the data obtained and the knowledge formed on their basis are stored.

2 Thesis 1: Why Bounded Rationality Solutions

Human behavior is based on the so-called. cognitive functions (attention, memory, perception, etc.), the carrier of which is the brain—an organ that combines the functions of controlling both biological and mental processes. From a formal point of view, such decisions are "fast", although not strictly optimal, since they allow "cognitive distortions" of physical models of situations and the context of events, but they allow taking into account: (1) previous experience, (2) operational data, (3) cognitive forecast possible consequences of the decisions made. In many cases, the use of heuristics leads to the so-called decisions of bounded rationality, which may differ significantly from decisions based on conscious, controlled, and analytically sound decisions. However, heuristics can be very effective in both practical and specific situations. In practice, cognitive biases occur when people apply heuristics in previously unknown or unfamiliar conditions that do not fit the existing model of space–time patterns and current contexts of events. In the process of brain evolution, the realization of cognitive functions was associated with the development of controls for specific biological, perceptual, and motor operations, which inevitably deviate from the abstract laws of logic, the theory of probability, or mechanics.

The control processes of such operations using the biological neural network of the brain and the central nervous system were aimed at solving a poorly formalized problem—to deliver a cognitive subject to where he could survive. For this, cognitive functions must effectively implement universal mechanisms for coincidence detection, pattern recognition, and associative learning, which are important for maintaining the physical integrity of the subject in the natural environment. Poorly formalized decisions of "bounded rationality" differ significantly from decisions obtained on the basis of "higher" cognitive functions, such as analytical and symbolic reasoning.

However, in the process of evolution, the brain has not been optimized for the implementation of the cognitive functions that provide the processes of analytical thinking (for example, calculation, statistics, analysis, reasoning, abstraction, conceptual thinking) and which have become important for the purposes of human "survival" only relatively recently. Therefore, the natural characteristics of the brain as a complex neural network adapted for the implementation of the functions of perception and motor skills require additional resources used in solving conceptual or analytical problems, which are based not on taking into account relative differences or comparisons, but on processing absolute values that characterize the phenomena under consideration. Understanding the mechanisms of cognitive processes associated with solving tasks for which the brain's neural network was initially optimized explains why a person can easily and effortlessly perform very computationally complex tasks of movement and perception (usually with massively parallel data flows), then has great difficulties in solving logical or arithmetic tasks, which are computationally much simpler.

3 Thesis 2: Computational Aspects

Cognitive processes of obtaining solutions of limited rationality give priority to information that is compatible and consistent with previously obtained knowledge while ignoring information that is not directly available or not recognized by the senses. There are four groups of cognitive distortions that determine the computability properties of cognitive functions, namely: association (correlations), compatibility, conservation, and attention. Currently, the greatest practical successes in solving intellectual problems have been achieved using methods that, in principle, are based on "brute computing force" or, in other words, on the ability to quickly sort possible solutions, for example, in analogy in playing chess. In our case, the "intellectualization" problem can be formulated as a solution to the inverse problem.

Many different options for representing such solutions in the form of a finite sequence of machine operations can be implemented in both inductive and deductive manners. In the first case, artificial neuromorphic computational structures are used, which are "programmed" by machine learning methods based on the previously classified dataset, and in the second case, digital platforms use target software libraries assembled from previously validated fragments. To concretize the task of building exo-intelligent platforms, we will rely on data aggregation and classification methods based on similarity criteria for objects or processes based on functional or structural associations, using the search for solutions based on the heterogeneous symbiosis of bio and machine intelligence resources shows on Fig. 1.

The basis of the technology of combining the computing resources of computer systems and the capabilities of human intelligence to solve P or NP complex tasks is the concept of mathematics of "big data". The "computational field" of such new math consists of (1) a tuple of "data-algorithms", (2) their meta characterization, and (3) resources of distributed heterogeneous reconfigurable computer platforms, the nodes of which are connected into the consistent system by "smart" data pass. Using the heterogeneity aspect of calculations, i.e. the use of processor elements with different architectures and set of operation, namely CPU, GPU, TPU, and FPGA [5], allows to effectively scale, both in "width" and "vertical", various algorithms of "extracting knowledge" from the processed data, "adjusting" taking into account the

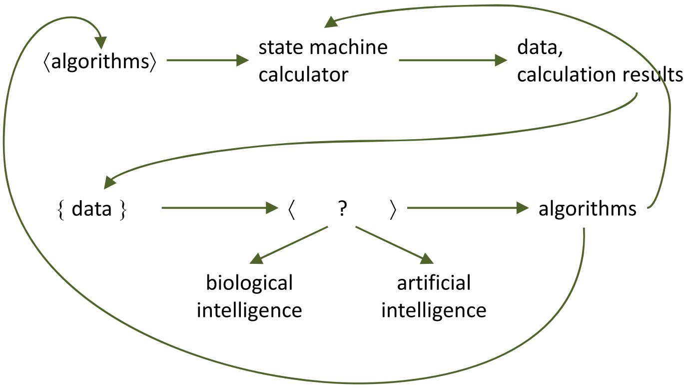

Fig. 1 The distribution between human and intelligence machine resources

situational context implemented a variety of algorithms that are used to assess potential threats and risks associated with the implementation of “calculated” solutions and the accuracy of computer models used [6].

It should be noted that due to heterogeneity and functional scaling, in exo-intelligent platforms, data processing algorithms oriented to the processor-centric approach can be effectively combined with memory-centric solutions, which allows simulating cognitive functions that can be characterized as “computational insight”, based on mechanisms to speed up the search algorithms by indexing the target data warehouse, potentially containing the whole spectrum of responses to correctly formulated queries. Similar mathematical processing technology is now widely used in modern search engines Yandex and Google, successfully modeling the functions of intellectual activity, which are usually associated with the concept of intuition. However, the technical implementation of this technology remains “flat,” that is, the adaptation of platform elements occurs only at the software level, when, as hardware components, they are formed from standard industrial systems.

This leads to a decrease in integrated energy-computational efficiency due to the fact that all modern processor elements at the macro level are built on the basis of logical gates AND-NOT or OR-NOT, therefore, any computational operations reduce the informational entropy of the processed data, contributing to the release of thermal energy no less than $Q = k * T * \ln 2$ J of energy, where k is the Boltzmann constant and T is the temperature of the system. This energy itself is small, so Q for $T = 300$ K is 0.017 eV per bit, but in terms of the number of logical elements (LE) which in the modern microprocessor (MP) is equal to $2–5 \times 1010$, the total energy at a switching frequency of LEs of 5 GHz grows to values of the order of 1 J for each second of MP operation. Therefore, if modern microprocessors combined in a supercomputer cluster, and try to simulate the work of the humane brain, which including 1.5×1017 LE, then the energy costs will exceed the level of practical expediency of using computer technologies, can be represented only of purely scientific interest.

Although reconfigurable computers have a higher specific energy efficiency of digital elements compared to MIMD microprocessors and SIMD graphics accelerators, FPGAs, however, perform work at much lower frequencies, which, however, expands the synthesis capabilities, allowing, or to reduce unit costs energy when achieving comparable performance, or at the same energy costs to obtain greater productivity of data processing processes through the use of special architectural solutions [7–10]. Achieving the technical and economic efficiency of using exo-intelligent platforms requires the search for solutions balanced in the aspect of "standardization-specialization", which, along with the effective implementation of standard computing procedures, have the resources necessary for using machine learning technologies and reconfiguring hardware accelerators taking into account the structural features of the implemented algorithms. In view of the foregoing, the transition to the use of technologies of hyper-converged clustering of heterogeneous processors, storage devices of a memory class, "smart" data channels endowed with intelligent processing functions, using specialized processors optimized for processing packet traffic, to create exo-intelligent platforms requires the development of universal heterogeneous computing modules that allow "vertical" and "horizontal" functional integration with the allocation of mutually agreed levels of "processing", "aggregation" and "explanation" of calculation results. An ex-intelligent solution based on a hyper-convergent processor/storage platform differs significantly from well-known approaches implemented in the framework of the "one program—a lot of data" model (SPM model), Amdahl-Ware phenomenological laws for programs with an invariable proportion of serial and parallel computing or the law Gustavson-Bors for programs that may be complicated due to the increase in the volume of processed data because they are based on the use of hardware reconfiguration methods, which are supported by machine learning algorithms.

The use of computational acceleration nodes as a basic component of the heterogeneous software and hardware reconfigurable platform extends its functionality by quickly adapting the hardware components to the features of Fig. 2 solution method, algorithms, and corresponding source code that is implemented at a given time.

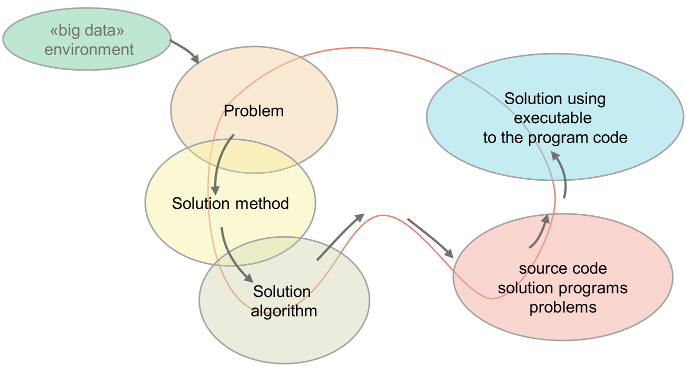

Fig. 2 Solution method, algorithms, and corresponding source code

4 Thesis 3: Discussion

Relentless digital transformation of modern knowledge, examples of which are supercomputer methods of predictive modeling, approximate optimization based on a random search, genetic algorithms based on meta-heuristics borrowed from nature, strictly speaking, form the components of a new exo-intellectual infrastructure for solving complex fundamental and applied tasks. This infrastructure is harmoniously supplemented by reinforcement machine learning methods, the formal prototypes of which are Robbinson-Monroe and Kiefer-Wolfowitz stochastic approximation methods, as well as other well-known random search numerical optimization methods. Although all these methods were actively developed long before the advent of AI tasks, their implementation on modern hyperconverged computing platforms opens up new possibilities for integrating the resources of the natural intelligence of people and artificial intelligence of "smart" machines [11–15]. The main capabilities of hyper-convergent high-performance computing platforms depend significantly on the balanced loading of all hardware components and the correspondence of their architecture to the specific features of the application programs.

Therefore, the proposed solution-wide is based on "machine learning" methods to associate hardware platforms as well as software components of cognitive function in order to increase boundary rationality solution accuracy as well as energy consumption.

With regard to computing platforms that are used to carry out cognitive operations in order to determine the associative features characteristic of the set of reversible data, Fig. 3 presented attractors of states of individual layers of the Siamese neural network, which allow, on the basis of their analysis of their structure, to judge whether the sister has achieved an "acceptable" rational solution.

5 Conclusions

The idea to clarify the essence of bounded rationality cognitive solutions in terms of computable functions and corresponding neuromorphic computing platform which architecture was chosen and parameters tuning by "machine learning" process that taking into account the specific features of heuristic algorithms can be very attractive due to significantly simplify harmonic integration with the associative "exo-intellectual" infrastructure that can adapt humane and machine resources. For the effective use of such an infrastructure, deep interdisciplinary training of computer science specialists is of particular importance, which requires the careful development of new education programs that cover both fundamental and applied aspects of the natural and engendering sciences, including the use of fundamental methods for predictive analytics, big data mathematics, and machine learning.

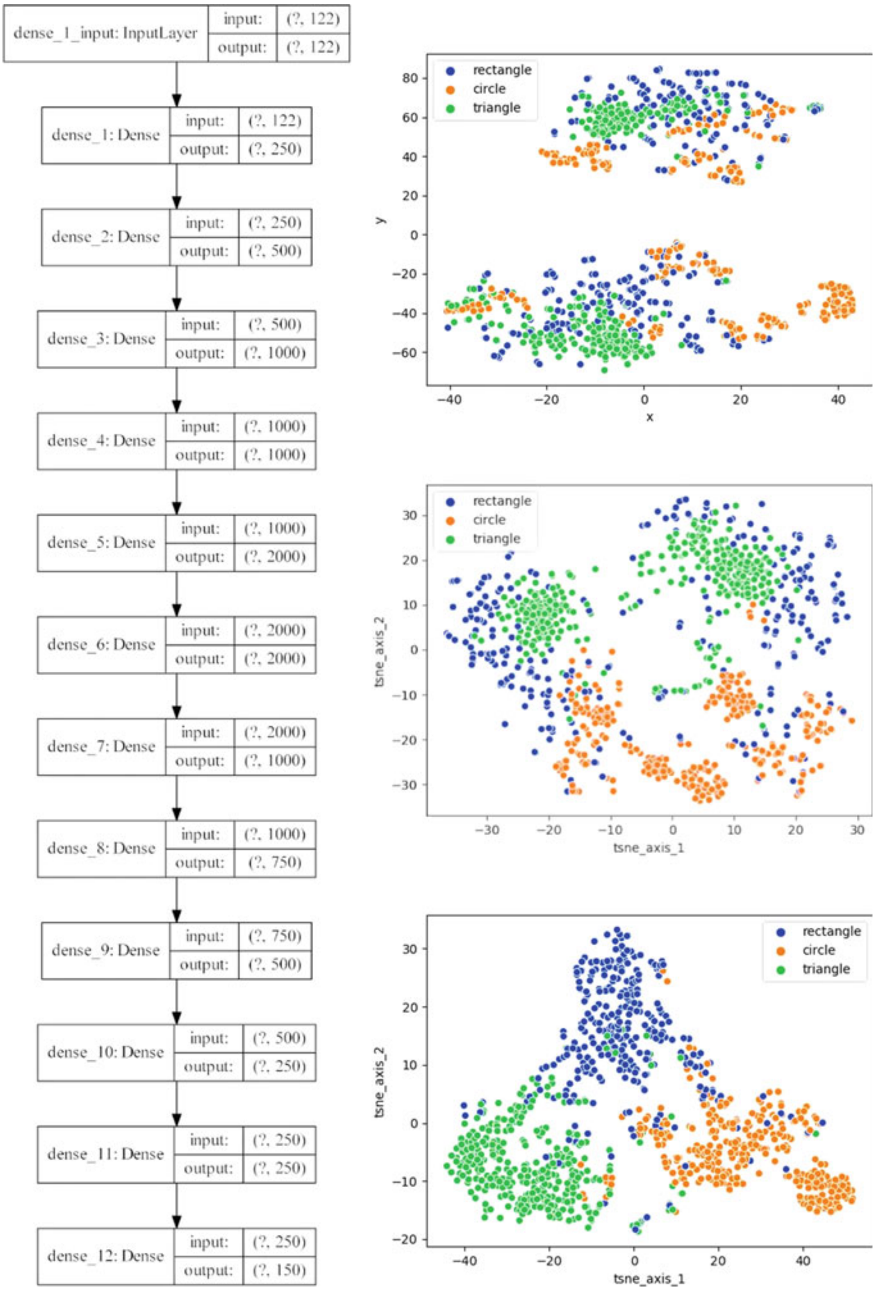

Fig. 3 Attractors of states of individual layers of the Siamese neural network

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