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LETTER

Parallel intelligence: toward lifelong and eternal developmental AI and learning in cyber-physical-social spaces

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Dear editor,
Fundamentally, there are only two main approaches so far in artificial intelligence (AI): reasoning-oriented formal logic approach and function-oriented computational intelligence approach, so called Neats vs. Scuruffies, which is a reflection of the historical fight between two schools of thought for formalism and empiricism respectively in the field of AI that is continuing even today. Here in this perspective, we present a third approach, the parallel intelligence (PI) approach [1–3], which was originally inspired by Immanuel Kant's Copernican revolution [4], Karl Popper's three worlds model of reality [5], Alfred Whitehead's process philosophy [6], Herbert Simon's theory of bounded rationality [7] and Marvin Minsky's principle of diversity for intelligence [8]. We believe PI provides both theoretical and technological foundations to support lifelong developmental AI and eternal learning through smart infrastructures constructed by cyber-physical-social systems (CPSS).

1 What is parallel intelligence?

The objective of PI is to establish a mechanism of acquiring, creating and supporting intelligence for parallel systems that consist of two or many pairs of actual physical systems and artificial software-defined systems [3,9,10]. Figure 1 presents the basic framework and process for PI systems, noting that the relationship between the actual and artificial systems can be one-to-one, one-to-many, many-to-one, and many-to-many, depending on the nature and complexity of the problem and the objectives of the solution.

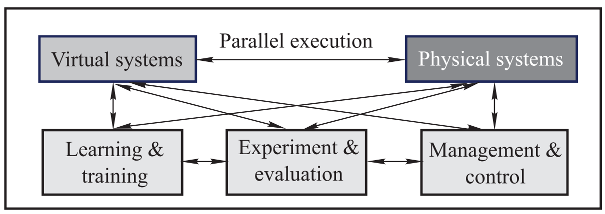

Fig. 1 The framework and process for PI

Intelligence development generally consists of four major issues: the paradigm (or pattern) of intelligence development, the intrinsic and extrinsic factors that affect intelligent development, the evaluation of intelligence, and the systematic approach of intelligence development. Mapping into the PI framework depicted in Fig. 1, the "paradigm of intelligence development" decides the approaches in "Learning & training" and "Experiment & evaluation". The "factors that affect intelligent development" decides the particular contents that PI utilizes for "Learning & training" and "Experiment & evaluation" functionalities. Through "evaluation of intelligence" being as system feedback, "Management & control" is achieved through interactions between virtual and real developmental intelligence systems. The whole real-

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virtual developmental intelligence implements the "systematic approach of intelligence development". Through the new PI based developmental AI, we aim to materialize descriptive intelligence that describes developmental states of AI, predictive intelligence that predicts the future development possibilities of AI, and prescriptive intelligence that guides the high-level development pathway of developmental AI.

2 Why parallel intelligence?

The development of information technology urged the emergence of big data; through big data technology, observation of complex systems is made feasible; through such feasibility, management and control of complex systems become possible. Analytic systems are usually described and analyzed by "big laws" (Newton's laws as a representative) and "small data" utilizing mathematical models. Large-scale systems rely on simulation models for analytics. The errors between real systems and models in analytic systems and large-scale systems are usually manageable, by introducing statistical or nonstatistical approaches. However, complex systems, especially the ones with societies and humans in the loop, are usually driven by Merton's law, resulting in difficulties of analyzing outcomes that vary with the prediction of system's future states from humans' mental world. As a result, it is usually difficult to model complex systems: the more complex a system is, the less accurate the model is, leading into a tremendous gap between the real world and the model world. This phenomenon is demonstrated in Fig. 2.

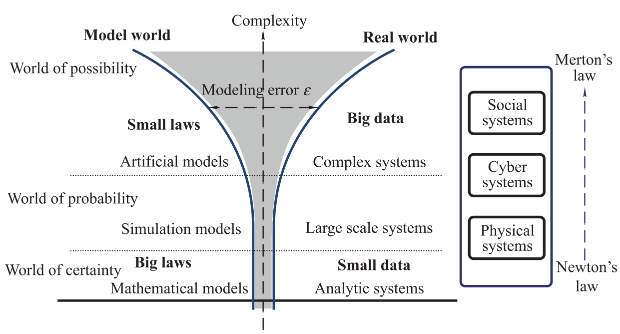

Fig. 2 Complexity vs.intelligence: the cognitive gap

In [3], we propose a system analytics paradigm shift from Church-Turing thesis to AlphaGo thesis, aiming at seeking a methodology of transforming "small data & big laws" to "big data & small laws" and then acquiring "small knowledge" that can be readily utilized by humans for specific tasks. This process is depicted in Fig. 3, describing the technical procedure of generating PI from data to intelligence.

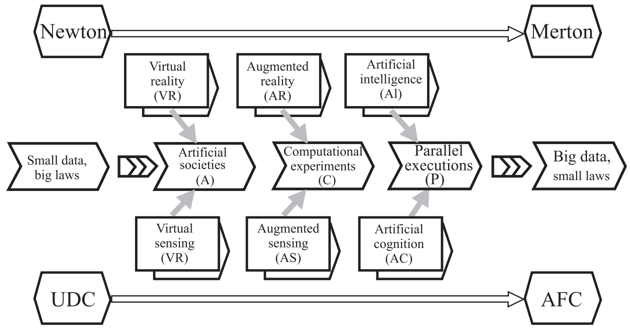

Fig. 3 From data intelligence to ACP-based parallel intelligence

3 Methods and infrastructures: ACP in CPSS

The methods and infrastructures of PI implementation are characterized by the ACP approach and CPSS infrastructure.

In ACP, "A" stands for "artificial systems", which works for building complex models; "C" denotes "computational experiments", which aims at data production and analytics; and "P" represents "parallel execution", which targets at innovative decision-making. The core philosophy of ACP is that, through combining "artificial systems", "computational experiments" and "parallel execution", one can utilize one or more virtual artificial spaces for solving complexity problems. The virtual artificial spaces and real physical space together construct the "complex space" for solving complex system problems.

The most recent development of intelligent technology, such as high-performance computing, high-throughput communication and Big Data analytics, provides a foundation for the ACP approach. In essence, the ACP approach aims to solve complex system problems through quantifiable and implementable real-time computation and interactions. In summary, the ACP approach consists of three major steps: 1) using artificial systems to describe complex systems; 2) using computational experiments to evaluate complex systems; and 3) interacting the real physical systems with the virtual artificial systems, and realizing effective control and management over complex systems. This whole process corresponds to descriptive intelligence, predictive intelligence and prescriptive intelligence, respectively.

CPSS provides the infrastructure of PI. The phrase of cyber-physical systems (CPS) aims to "describe the tight conjoining of and coordination between computational (or cyber) and physical resources, that is, systems that feature a tight integration between computation, communication, and control in their operation and interactions with the task environment