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Cognitive Informatics:

Towards Cognitive Machine Learning and Autonomous Knowledge Manipulation

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ABSTRACT

Cognitive Informatics (CI) is a contemporary field of basic studies on the brain, computational intelligence theories and underpinning denotational mathematics. Its applications include cognitive systems, cognitive computing, cognitive machine learning and cognitive robotics. IEEE ICCI*CC'17 on Cognitive Informatics and Cognitive Computing was focused on the theme of neurocomputation, cognitive machine learning and brain-inspired systems. This paper reports the plenary panel (Part I) at IEEE ICCI*CC'17 held at Oxford University. The summary is contributed by invited keynote speakers and distinguished panelists who are part of the world's renowned scholars in the transdisciplinary field of CI and cognitive computing.

KEYWORDS

Applications, Artificial Intelligence, Brain-Inspired Systems, Cognitive Computers, Cognitive Engineering, Cognitive Informatics, Cognitive Robotics, Cognitive Systems, Computational Intelligence, Deep Learning, Deep Reasoning, Denotational Mathematics, Knowledge Learning

1. INTRODUCTION

Cognitive Informatics (CI) is a transdisciplinary enquiry of the internal information processing processes of the brain and abstract intelligence towards applications in cognitive computing and cognitive engineering (Wang, 2002, 2003, 2007a, 2009a, 2009b, 2009c, 2011b, 2012e, 2013c, 2015a, 2016a, 2017a; Wang et al., 2009, 2010, 2016; Howard et al., 2017). CI is a contemporary field spanning across computer science, information science, cognitive science, brain science, neuroscience, intelligence science, knowledge science, robotics, cognitive linguistics, cognitive philosophy, and

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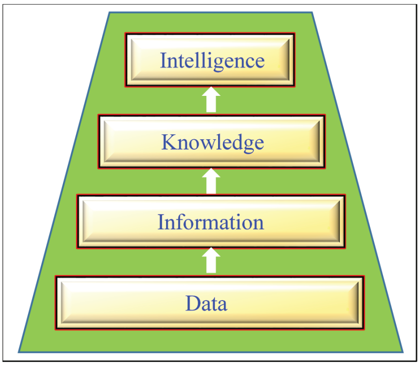
cognitive engineering. Cognitive Computing (CC) is a novel paradigm of intelligent computing platforms of cognitive methodologies and systems based on CI, which embodying computational intelligence by cognitive and autonomous systems mimicking the mechanisms of the brain (Wang, 2002, 2007a; Wang et al., 2002, 2007a, 2009a, 2009b, 2016a, 2017a).

The IEEE series of *International Conferences on Cognitive Informatics and Cognitive Computing* (ICCI*CC) has been established since 2002 (Wang, 2002; Wang et al, 2002). Since its inception, the ICCI*CC series has been growing steadily in its size, scope, and depth. It has attracted worldwide researchers from academia, government agencies, and industry practitioners. The IEEE ICCI*CC series provides a main forum for the exchange and cross-fertilization of ideas in the new research field of CI toward revealing the cognitive mechanisms and processes of human information processing and the approaches to mimic them in cognitive computing. A wide range of breakthroughs have been recognized and a wide range of applications has been developed in CI and CC in the last decade. The representative paradigms and technologies developed in cognitive informatics include cognitive computers, abstract intelligence, cognitive learning engines, cognitive knowledge bases, denotational mathematics and applied cognitive systems.

CI studies the cognitive objects represented in the brain in the categories of data, information, knowledge and intelligence by a hierarchical structure (Berkeley, 1954; Turing, 1950; Shannon, 1948; von Neumann, 1958; McCulloch, 1965; Debenham, 1989; Wang, 2009a, 2014a, 2015f). The relationship between the four categories of cognitive objects in the hierarchical framework of human cognition is illustrated in Figure 1 (Wang, 2016b). It is perceived that data are acquired raw information which are usually a quantitative abstraction of external entities and their relations. Information is meaningful data or an interpretation of data. Knowledge is consumed information related to existing knowledge in the brain. Intelligence is a collection of cognitive abilities of humans or cognitive systems that transforms information into behaviors (Wang, 2012c). Rigorous models and mathematical manipulations on intelligence, knowledge, information and data are formally described in (Wang, 2015f).

Fundamental theories of CI cover the Matter-Energy-Information-Intelligence (MEII) model (Wang, 2015g), the Layered Reference Model of the Brain (LRMB) (Wang et al., 2006), the Object-Attribute-Relation (OAR) model of internal information and knowledge representation (Wang, 2007c), the Cognitive Functional Model of the Brain (CFMB) (Wang & Wang, 2006), Abstract Intelligence (αI) (Wang, 2009a, 2012c), Neuroinformatics (Wang, 2013a; Wang and Fariello, 2012), Denotational Mathematics (Wang, 2008, 2009d, 2012a,b), Cognitive Linguistics (Wang & Berwick, 2012, 2013), the Spike Frequency Modulation (SFM) Theory of neural signaling (Wang, 2016h), the Neural Circuit Theories (Wang, 2017; Wang and Fariello, 2012), and cognitive systems (Wang et al., 2017). Recent studies on LRMB in CI reveal an entire set of cognitive functions of the brain and their cognitive

Figure 1. The hierarchical framework of cognitive objects in CI



process models, which explain the cognitive mechanisms and processes of the natural intelligence with 52 cognitive processes at seven layers known as the sensation, action, memory, perception, cognitive, inference, and intelligence layers (Wang et al., 2006).

IEEE ICCI*CC'17 on Cognitive Informatics and Cognitive Computing has been held at Oxford University during July 26-28, 2017 (Howard et al., 2017). This paper is a summary of the position statements of invited panellists presented in the *Plenary Panel* of IEEE ICCI*CC 2017 *on Neurocomputation, Cognitive Machine Learning and Brain-Inspired System* (Part I). It is noteworthy that the individual statements and opinions included in this paper may not necessarily be shared by all panellists.

2. A BETTER MODEL FOR A COMPLEX BRAIN

There is a growing conundrum in modern medicine; disorders need to be healed and people need to feel better, however most practitioners do not understand the physiology of the disorders the are treating or the treatment they are prescribing. Most clinicians have a basic understanding; however, the brain is too complex for a "one size fits all" operating model and each person's polymorphisms of various receptors are different. There is no clear, standardized pattern. One person's depression could be another's anxiety. A case that appears to be depression could in fact be a serotonin issue, or a norepinephrine issue, or a glutamate issue, or a transporter problem or an auto receptor, or some other unknown mechanism, or any combination of these could be the cause. People respond differently to different medications. A lot of trial and error and clinical instinct are required to reach a level of efficacy. There needs to be a better brain model that takes into account the brain's function and output at several levels simultaneously: from elector-physiology to molecular mechanisms of information storage and signaling, to the multi-scale neural network formation and trends.

The fields of neuroinformatics and connectomics have made great strides in functional and structural brain mapping. However, limited value of those results has been clinically applied, and it largely remains a mystery how rich functionality emerges from the invariant structural architecture of the brain. Understanding brain function and dysfunction requires a multidisciplinary approach and various methodologies ranging from biology to mathematics. One of the biggest challenges is decoding how the brain and its neurons are structured and how they function. This information is crucial for better understanding normal brain function and possibly uncovering causes of brain disorders. However, this decoding requires extraction and integration of massive amounts of data of different types, across different spatio-temporal scales and across different levels of brain function, a field called neuroinformatics. Specifically, neuroinformatics is the study of understanding the complex human brain, which functions at several different levels (i.e. genetics, cellular, electrophysiological, behaviorial). Closely related, connectomics permits the opportunity to produce maps of neural connectivity in and between different brain regions. Neuroinformatics and Connectomics both encompass mapping functional and structural information of the entire brain.

Today's technologies to collect multi-level data exist across spatial scales, from electron microscopy to whole-brain imaging, and time scales ranging from microseconds to years. It is not exactly clear how to efficiently integrate these diverse data. Given the volume of data from these undertakings, it is important to analyze and integrate all the data in a common platform at different spatio-temporal scales and various neural levels. One of the biggest challenges in neuroinformatics is analyzing imaging data across different spatial-scales and integrating all of the multi-level spatial information into one framework.

The Fundamental Code Unit (FCU) (Howard, 2012; Howard, 2013b) attempts to describe an analytical framework that serves as a medical aggregation platform for multiple levels of neural data. The FCU describes architecture of spatiotemporal integration across all levels of brain structure and function. The FCU is an analytical model that uses sequence and coding to explain and predict brain structure and function. The FCU framework not only maps brain structure, but also the cognitive and behavioral output that is produced, it also attempts to map structural and functional networks to a theoretical system that bridges the gap between the mind the behavior (or consciousness and/or thought) and the brain. The brain being the biological, chemical and physical basis of the mind. The Fundamental Code Unit (FCU) assumes an abstract code that allows for a higher order of abstractions that informs cortical computing underlying information exchanges at the cellular and genetic levels.

Regardless of the tools used to collect data, the FCU platform should be able to extract and integrate multiple types, levels and timescales of data in order to find statistically interesting functional and structural patterns that link to higher cognitive functions and behavioral observable at a clinical level. Whereas most models of brain function acknowledge neurons, or the interaction between them as the most basic unit, the FCU suggests a metaphysical schema of basic operating principles. In this regard, the FCU could serve as a blueprint of cognition, similar to how DNA is the blueprint for proteins that drive biological processes. One potential clinical application of the FCU framework is to determine objective measures of psychiatric and neurological disorder by integrating and decoding data across spatiotemporal scales and across multiple levels of brain function. (*This section is contributed by Prof. Newton Howard.*)

3. THE POWER OF COGNITIVE COMPUTING: AN EXAMPLE OF COGNITIVE DYNAMIC REGIONAL DEVELOPMENT MODELING

This presentation concerns some idea of what could be done, in the author's view, to help make Wang's cognitive informatics a powerful and viable source of tools and techniques for solving various real-life problems. First, we give a brief account of cognitive informatics meant as a multidisciplinary field within informatics, or computer science, that is based on results of cognitive and information sciences, and which deals with human information processing mechanisms and processes and their decision theoretic, engineering, etc. applications in broadly perceived computing. We focus on its purpose, i.e. to develop and implement technologies to facilitate and extend the information acquisition, comprehension and processing capacity of humans. Emphasis is on underlying processes in the brain.

However, we advocate an extended approach in which though the very cognitive informatics is the foundation, as those processes in the brain are crucial, some sort of an "outer" cognitive informatics is needed which explicitly makes reference not what proceeds "internally" in the brain, because we do not "see" this, but "externally", i.e. what people can see, judge, evaluate, etc., and what is clearly a result of cognitive information specific processes in the brain.

This line of reasoning is in line with the very essence of comprehension, memorizing, learning, choice and decision making, satisfaction with partial truth, allowing for not perfect solutions, etc. dealt with using tools and techniques derived from many areas like psychology, behavioral science, neuroscience, artificial intelligence, linguistics, neuroeconomics etc. In our case, we will concentrate on some cognitive informatics type elements that mostly have been inspired by psychology and behavioral sciences, as our problem is inherently related to human judgments and perceptions, but we will mention some inspirations from neuroscience, notably along the lines of neuroeconomics.

Cognitive informatics constitutes a foundation of its related new field, cognitive computing, which is basically a new direction in broadly perceived intelligent computing and systems that synergistically combines results from many areas, e.g., information science, computational sciences, computer science, artificial and computational intelligence, cybernetics, systems science, cognitive science, (neuro)psychology, brain science, linguistics, etc. to just mention a few.

We try to show on an example of a dynamic systems modeling, more specifically scenario based regional development planning, that cognitive computing can provide new conceptual and implementation vistas. Basically, we consider a region that is characterized by 7 life quality indicators related to economic, social, environmental, etc. qualities, which evolve over some planning horizon due to some investments, mostly by some regional or governmental agencies. There are some scenarios of investment levels over the planning horizon, meant for the development of the particular life quality indexes, and some desired levels of these indexes, both objective, i.e. set by authorities, and subjective, i.e. perceived by the inhabitant groups. As a result of a particular investment scenario, the life quality indexes evolve over the planning horizon, and their temporal evolution is evaluated by the authorities and inhabitants. This evaluation has both an objective, i.e. against the “officially” set thresholds, and subjective, i.e. as perceived by various humans and their groups.

Basically, we employ Kacprzyk’s fuzzy dynamic programming based approach to the modeling and planning/programming of sustainable regional development, with soft constraints and goals, but we advocated a more sophisticated assessment of variability, stability, balancedness of consecutive investments. In this process we try to develop evaluation measures, and then the optimization type model using concepts that can be effectively and efficiently handled by cognitive computing, notably the inclusion of the so-called decision making and behavioral biases, biases in probability and belief, social biases, memory errors, etc. Moreover, we strongly reflect the so-called status quo and minimal change biases. By using many results from social sciences, psychology, behavioral economics, neuroeconomics, etc. on human judgments and human centric evaluations, we augment a traditional purely effectiveness and efficiency oriented analysis by a more sophisticated analysis of effects of variability of temporal evolution of some life quality indicators on the human perception of its goodness.

The model presented, which has been employed for years as part of large mathematical modeling projects for sustainable regional development in many regions in Asia and Europe, is illustrated on an example with scenario analysis for a rural region plagued by social and economic difficulties in which subsidies should properly be distributed over time to obtain a best overall socio-economic effect. In this talk we present the model in a different perspective, based first on the basic Wang’s cognitive informatics and its Wang and Ruhe’s decision making application, and then based on new, more comprehensive cognitive computing. We show that this provides a novel insight. (*This section is contributed by Prof. Janusz Kacprzyk.*)

4. RETHINK AND REUSE: WORKING OUTSIDE ONE’S DOMAIN OF UNDERSTANDING

So much about intelligence is unknown that capitalizing on what one already knows, potentially viewing previous knowledge in a different light, is opportunistic and advantageous. In that vein, we briefly highlight three applications solved using computational tools designed for vastly different domains: radiological readings discrepancies detection; disease outbreak forecasting; and urinary tract infection treatment.

Using machine language translation techniques, we describe automated means to detect radiological readings inconsistencies. By translating initial to final readings, inconsistencies are flagged and evaluated in terms of their differences. Then, social media trend detection is used to detect and forewarn disease outbreak in disease susceptible population. Finally, using conventional data mining techniques an unconventional urinary tract infection treatment approach was developed. (*This section is contributed by Prof. Ophir Frieder.*)

5. SEMANTIC COMPUTING AND COGNITIVE COMPUTING/INFORMATICS

Semantic Computing (SC) addresses the derivation, description, integration, and use of semantics (“meaning”, “context”, “intention”) for all types of resource including data, document, tool, device, process and people. A broader definition of Semantic Computing includes the computing technologies (e.g., artificial intelligence, natural language, software engineering, data and knowledge engineering, computer systems, signal processing, etc.), and their interactions, that may be used to extract or process computational content.

This connection between content and the user is made via Semantic Analysis, which analyzes content with the goal of converting it to machine processable descriptions (semantics); Semantic Integration, which integrates content and semantics from multiple sources; Semantic Applications, which utilize content and descriptions to solve problems; and Semantic Interface, which interprets users' intentions expressed in natural language or other communicative forms. The reverse connection converts the intentions of users to create content via analysis and synthesis techniques. My talk introduces Semantic Computing based on its broader and narrower definitions, its relationship with Artificial Intelligence, Cognitive Computing and Informatics, and other branches of Computer Science. It also discusses several case studies showing how it can be used to solve more complex problems. (*This section is contributed by Prof. Phillip Sheu.*)

6. BRAIN-INSPIRED SYSTEMS AND COGNITIVE BOLDNESS

In his epoch-making work on communication theory, Shannon defined information in terms of entropy. Shannon's entropy is a fast stochastic measure of probabilistic information uncertainty in every communication processing system. It is the average unpredictability of a random variable (Shannon, 1948). Entropy-based definitions of information relate to quantity of information, but not to its meaning. Subsequent attempts to introduce semantics into information theory have made some progress but fell short of having a capability to deal with information described in natural language. According to L. A. Zadeh, a theory of semantic information (TSI) is centered on a concept which plays a key role in human intelligence. A concept whose basic importance has long been and continues to be unrecognized. The concept of a restriction is pervasive in human cognition (Zadeh, 2008). Restrictions underlie the remarkable human ability to reason and make rational decisions in an environment of imprecision, uncertainty and incompleteness of information. Such environments are the norm in the real-world. Such environments have the traditional logical systems that become dysfunctional by the current systemic approach based on the usual predicative and narrative perspective. A fundamental issue in TSI is computation with restrictions to achieve a clear meaning. TSI opens the door to modes of computation in which approximation is accepted. Acceptance of approximate computations takes the calculus of restrictions (CR) into uncharted territory (Zadeh, 1965, 1975, 1997, 2004, 2008, 2016). In fact, approximation can be of two fundamental different types. Either approximated approximation or exact approximation. They immediately give birth to two large areas of structured language systems, i.e. arbitrary entropy representation languages and minimum entropy representation languages. This is the difference that makes the difference (Bateson, 1972) at semantic level!

The current scientific inability to discriminate this difference makes a big difference in the final formulation of the logical relationship between human experience and knowledge extraction. This incompetence has been identified and underlined by the formulation of the information double-bind (IDB) problem in current science in 2013. It has been presented recursively to the scientific community by R. A. Fiorini (Fiorini, 2014a, 2014b, 2016a, 2016b, 2018; Wang et al., 2016b), but nobody in the traditional scientific arena likes to talk about it seriously. Therefore, cognitive ambiguity still emphasizes this major IDB problem in most current, advanced research laboratory and instrumentation system, just at the inner core of human knowledge extraction by experimentation in science (Fiorini, 2014a, 2014b). This is the main reason why traditional computational resources and systems have still to learn a lot from human brain-inspired computation and reasoning. If we, as Cognitive Informatics and Cognitive Computing Society, do really want to create the right, vital environment to develop a real, solid TSI, we, as a scientific community, must find the cognitive boldness to embrace, to face and solve this problem successfully. Then everything else will be a gentle breeze. (*This section is contributed by Prof. Rodolfo A. Fiorini.*)

7. BRAIN INSPIRED BIOMETRIC SYSTEMS

Machine learning and cognitive systems can be used as a powerful tool for understanding behavioral patterns expressed over time. They also can be used for training the brain-inspired systems to recognize those traits in real time and to use this knowledge not only for user identification, but also to better understand user preferences, habits, health status, and even emotional state. Traits for analysis can be visual, signal-based and even aesthetic based. There are numerous applications of the social behavioral biometrics aside from the person authentication, which may include virtual world simulators, augmented reality, virtual human research, customer profiling, e-education, situation awareness, recommender systems, games and consumer electronics. Biometric Technologies Laboratory at the University of Calgary pioneered the research in the Social Behavioural Biometrics, where online network users' social traits are studied with the goal of understanding discriminative traits, which can be used for user recognition.

Combined with new image and signal processing methods, and powerful cognitive architectures based on fuzzy logic, information fusion, deep learning, local and global feature extractions methods, and powerful brain-inspired architectures, the social behavioural research goes further than ever before. It is well known that emotional responses, adaptive behaviour, complex decision making, contextual information processing and emotional associations play a significant role in how human recognize each other. This in turn, paved the way for the next generation biometric systems that can adaptively expand behavioural pattern collection as well as learn new knowledge by analysing multi-dimensional information over time. (*This section is contributed by Prof. Marina Gavrilova*.)

8. THE TREND OF COMPUTATIONAL INTELLIGENCE WITH IOT

Commercialization of Computational Intelligence (CI) with Internet of Things (IoT) has already being rapidly advancing nowadays. For Computational Intelligence, the most important task of IoT is actually data collection, where IoT connects a large number of different devices, including home appliances and wearable devices. The sensors embedded in each device constantly upload new data to the cloud. The data can be processed and analyzed by computational intelligence to generate the required information and continue to accumulate knowledge. The development of computational intelligence is inseparable from massive data training. At present, deep learning is mainly based on big data for training and deducing the knowledge or rules that can be used by computers. From now on, big data would be the cornerstone of computational intelligence. Therefore, it can be said that IoT techniques make computational intelligence more powerful. On the other hand, IoT without computational intelligence cannot serve humanity better. (*This section is contributed by Prof. Jun Peng*.)

9. COGNITIVE FOUNDATIONS OF KNOWLEDGE SCIENCE AND DEEP KNOWLEDGE LEARNING BY COGNITIVE ROBOTS

Recent basic studies reveal that novel solutions to fundamental AI problems are deeply rooted in both the understanding of the natural intelligence and the maturity of suitable mathematical means for rigorously modeling the brain in machine understandable forms. Learning is a cognitive process of knowledge and behavior acquisition. Learning can be classified into six categories known as: object identification, cluster classification, pattern recognition, functional regression, behavior generation (game playing), and knowledge acquisition. The latest discovery in knowledge science by Wang revealed that the basic unit of knowledge is a binary relation (*bir*) (Wang, 2016b) as that of *bit* for information and data. A fundamental challenge to knowledge learning different from those of deep and recurring neural network technologies has led to the emergence of the field of cognitive machine learning on the basis of recent breakthroughs in denotational mathematics and mathematical engineering.

The latest advances in formal brain studies and cognitive systems reveal that key technologies enabling cognitive robots mimicking the brain rely not only on deep learning, but also on deep reasoning and thinking towards machinable thoughts and cognitive knowledge bases built by cognitive systems. Fundamental theories and novel technologies for implementing deep thinking robots are demonstrated based on concept algebra, semantics algebra and inference algebra, because the domain of problems in this field has natural grown beyond the classic mathematical domain of pure numbers, which is identified as hyperstructures (Wang, 2015a, 2016c) such as systems, knowledge, concepts, semantics, inference threads, relations and intelligence.

Towards exploring the cognitive foundations of knowledge science, a set of formal models of knowledge has been created. The mathematical theories of knowledge have enabled a rigorous study on formal principles and rules of knowledge in the facets of the hierarchical, compositional, cognitive, and sociological properties of knowledge. It has been revealed that the basic cognitive structure of knowledge is a formal concept and the basic unit of knowledge is a binary relation (*bir*). The basic studies have led to a set of fundamental theories towards knowledge science and a wide range of applications in knowledge engineering such as cognitive knowledge base and cognitive machine learning. (*This section is contributed by Prof. Yingxu Wang and Prof. Shushma Patel.*)

10. CONCLUSION

This paper has summarized a set of position statements presented in the plenary panel (Part I) of IEEE ICCI*CC'17 on neurocomputation, cognitive machine learning and brain-inspired systems, which were contributed by renowned panelists in the contemporary field of cognitive informatics and cognitive computing. It has been elaborated that the theoretical foundations underpinning cognitive computing are cognitive informatics, the science of cognitive information and knowledge processing, as well as denotational mathematics. A wide range of theoretical breakthroughs and novel engineering applications has been reported. The former is represented by such as cognitive informatics theories of the brain, the abstract intelligence (αI) theory, the sixth category of machine knowledge learning, cognitive knowledge bases, and denotational mathematics for mathematical engineering. The latter are demonstrated by cognitive computing methodologies, cognitive robots, deep learning machines, cognitive learning engines, cognitive systems, autonomous ontology generation, and cognitive self-driving cars.

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