Cognitive Informatics and Cognitive Computing in Year 10 and Beyond

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Yingxu Wang
The University of Calgary

Robert Berwick
Massachusetts Institute of Technology

Witold Kinsner
University of Manitoba

George Baciu
The Hong Kong Polytechnic University

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Yingxu Wang, University of Calgary, Canada

Robert C. Berwick, Massachusetts Institute of Technology, USA

Simon Haykin, McMaster University, Canada

Witold Pedrycz, University of Alberta, Canada

Witold Kinsner, University of Manitoba, Canada

George Baciu, Hong Kong Polytechnic University, Hong Kong

Du Zhang, California State University, Sacramento, USA

Virendrakumar C. Bhavsar, University of New Brunswick, Canada

Marina Gavrilova, University of Calgary, Canada

ABSTRACT

*Cognitive Informatics (CI) is a transdisciplinary enquiry of computer science, information sciences, cognitive science, and intelligence science that investigates into the internal information processing mechanisms and processes of the brain and natural intelligence, as well as their engineering applications in cognitive computing. The latest advances in CI leads to the establishment of cognitive computing theories and methodologies, as well as the development of Cognitive Computers (CogC) that perceive, infer, and learn. This paper reports a set of nine position statements presented in the plenary panel of IEEE ICCI*CC'11 on Cognitive Informatics in Year 10 and Beyond contributed from invited panelists who are part of the world's renowned researchers and scholars in the field of cognitive informatics and cognitive computing.*

Keywords: *Algebra, Artificial Intelligence, Cognitive Computing, Cognitive Informatics, Computational Intelligence, Denotational Mathematics, Industrial Applications, Natural Intelligence, Visual Semantic Algebra*

1. INTRODUCTION

The theories of informatics and their perceptions on the object of information have evolved from the classic information theory, modern informatics, to cognitive informatics in the last six de-

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cades. The *classic information theories* (Shannon & Weaver, 1949; Bell, 1953; Goldman, 1953), particularly Shannon's information theory (Shannon, 1948), are the first-generation informatics, which study signals and channel behaviors based on statistics and probability theory. The *modern informatics* studies information as properties or attributes of the natural world that can be distinctly elicited, generally abstracted, quantitatively represented, and mentally processed (Wang, 2002a, 2003a, 2003b). The first- and second-generation informatics put emphases on external information processing, which are yet to be extended to observe the fundamental fact that human brains are the original sources and final destinations of information. Any information must be cognized by human beings before it is understood, comprehended, and consumed.

The aforementioned observations have led to the establishment of the third-generation informatics, *cognitive informatics* (CI), a term coined by Wang in a keynote in 2002 (Wang, 2002a). CI is defined as the science of cognitive information that investigates into the internal information processing mechanisms and processes of the brain and natural intelligence, and their engineering applications via an interdisciplinary approach. It is recognized in CI that *information* is the third essence of the natural world supplementing to matter and energy. *Informatics* is the science of information that studies the nature of information, its processing, and ways of transformation between information, matter and energy.

The IEEE series of *International Conferences on Cognitive Informatics and Cognitive Computing* (ICCI*CC) has been established since 2002 (Wang, 2002a; Wang et al., 2002). The inaugural ICCI event in 2002 was held at University of Calgary, Canada (ICCI'02) (Wang et al., 2002), followed by the events in London, UK (ICCI'03) (Patel et al., 2003); Victoria, Canada (ICCI'04) (Chan et al., 2004); Irvine, USA (ICCI'05) (Kinsner et al., 2005); Beijing, China (ICCI'06) (Yao et al., 2006); Lake Tahoe, USA (ICCI'07) (Zhang et al., 2007); Stanford University, USA (ICCI'08) (Wang et al., 2008); Hong Kong (ICCI'09) (Baciu et al., 2009); Tsinghua University, Beijing (ICCI'10) (Sun et al., 2010); and Banff, Canada (ICCI*CC'11) (Wang et al., 2011). Since its inception, the ICCI*CC series has been growing steadily in its size, scope, and depth. It attracts worldwide researchers from academia, government agencies, and industry practitioners. The conference 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 series of fundamental breakthroughs have been recognized and a wide range of applications has been developed in cognitive informatics and cognitive computing in the last decade. The representative paradigms and technologies developed in cognitive informatics are such as cognitive computing, cognitive computers, abstract intelligence, formal knowledge representation, cognitive learning engines, denotational mathematics for cognitive system modeling, and applicants in cognitive systems.

This paper is a summary of the position statements of panellists presented in the *Plenary Panel on Cognitive Informatics in Year 10 and Beyond* in IEEE ICCI*CC 2011 held in Banff, Alberta, Canada during August 18-20, 2011 (Wang et al., 2011). It is noteworthy that the individual statements and opinions included in this paper may not necessarily be shared by all panellists.

2. THE FRAMEWORK OF COGNITIVE INFORMATICS AND COGNITIVE COMPUTING

The framework of cognitive informatics (Wang, 2003a, 2007b) and cognitive computing (Wang, 2006, 2009b, 2010a; Wang, Zhang, & Kinsner, 2010) can be described by the following theories, mathematical means, cognitive models, computational intelligence technologies, and applications.

Fundamental Theories of Cognitive Informatics

Cognitive Informatics (CI) is a transdisciplinary enquiry of computer science, information science, cognitive science, and intelligence science that investigates into the internal information processing mechanisms and processes of the brain and natural intelligence, as well as their engineering applications in cognitive computing (Wang, 2002a, 2003a, 2006, 2007b, 2007d, 2009a, 2009b; Wang & Kinsner, 2006; Wang & Wang, 2006; Wang, Zhang, & Kinsner, 2010; Wang, Kinsner, & Zhang, 2009; Wang, Kinsner et al., 2009).

CI is a cutting-edge and multidisciplinary research area that tackles the fundamental problems shared by computational intelligence, modern informatics, computer science, AI, cybernetics, cognitive science, neuropsychology, medical science, philosophy, formal linguistics, and life science (Wang, 2002a, 2003a, 2007b). The development and the cross fertilization among the aforementioned science and engineering disciplines have led to a whole range of extremely interesting new research fields known as CI, which investigates the internal information processing mechanisms and processes of the natural intelligence – human brains and minds – and their engineering applications in computational intelligence. CI is a new discipline that studies the natural intelligence and internal information processing mechanisms of the brain, as well as processes involved in perception and cognition. CI forges links between a number of natural science and life science disciplines with informatics and computing science.

Fundamental theories developed in CI covers the Information-Matter-Energy-Intelligence (IME-I) model (Wang, 2007a), the Layered Reference Model of the Brain (LRMB) (Wang et al., 2006), the Object-Attribute-Relation (OAR) model of internal information representation in the brain (Wang, 2007c), the cognitive informatics model of the brain (Wang & Wang, 2006), natural intelligence (Wang, 2007b), abstract intelligence (Wang, 2009a), neuroinformatics (Wang, 2007b), denotational mathematics (Wang, 2002b, 2007a, 2008a, 2008b, 2008c, 2008d, 2009c, 2009d, 2009e, 2010b, 2011, in press; Wang, Zadeh, & Yao, 2009), and cognitive systems (Berwick, 2011; Haykin, 2011; Kinsner, 2011; Pedrycz, 2011; Wang, 2011). Recent studies on LRMB in cognitive informatics reveal an entire set of cognitive functions of the brain and their cognitive process models, which explain the functional mechanisms and cognitive processes of the natural intelligence with 43 cognitive processes at seven layers known as the sensation, memory, perception, action, meta-cognitive, meta-inference, and higher cognitive layers (Wang et al., 2006).

Cognitive Computing for Cognitive Computers

Computing systems and technologies can be classified into the categories of *imperative*, *autonomic,* and *cognitive* computing from the bottom up. The imperative computers are a passive system based on stored-program controlled behaviors for data processing (Wang, 2009b). The autonomic computers are goal-driven and self-decision-driven machines that do not rely on instructive and procedural information (Pescovitz, 2002; Wang, 2007d). Cognitive computers are more intelligent computers beyond the imperative and autonomic computers, which embody major natural intelligence behaviors of the brain such as thinking, inference, and learning.

Cognitive Computing (CC) is a novel paradigm of intelligent computing methodologies and systems based on CI that implements computational intelligence by autonomous inferences and perceptions mimicking the mechanisms of the brain (Wang, 2006, 2009b, 2009c, 2010a; Wang, Tian, & Hu, 2011). CC is emerged and developed based on the multidisciplinary research in CI (Wang, 2002a, 2003, 2007b; Wang, Zhang, & Kinsner, 2010; Wang, Kinsner et al., 2009).

The latest advances in CI and CC, as well as denotational mathematics, enable a systematic solution for the future generation of intelligent computers known as *cognitive computers* (CogCs) that think, perceive, learn, and reason (Wang, 2006, 2009b, 2009c, 2010a; Wang, Zhang, & Kinsner, 2010; Wang, Widrow et al., 2011). A CogC is an intelligent computer for knowledge processing as that of a conventional von Neumann computer for data processing. CogCs are designed to embody *machinable intelligence* such as computational inferences, causal analyses, knowledge manipulation, machine learning, and autonomous problem solving.

Recent studies in cognitive computing reveal that the computing power in computational intelligence can be classified at four levels: *data, information, knowledge,* and *intelligence* from the bottom up. Traditional von Neumann computers are designed for imperative data and information processing by stored-program-controlled mechanisms. However, the increasing demand for advanced computing technologies for knowledge and intelligence processing in the high-tech industry and everyday lives require novel cognitive computers for providing autonomous computing power for various cognitive systems mimicking the natural intelligence of the brain.

Abstract Intelligence (αI)

The studies on abstract intelligence (αI) form a human enquiry of both natural and artificial intelligence at reductive levels of the neural, cognitive, functional, and logical layers from the bottom up (Wang, 2009a). αI is the general mathematical form of intelligence as a natural mechanism that transfers information into behaviors and knowledge.

The *Information-Matter-Energy-Intelligence* (IME-I) model (Wang, 2003a, 2007c) states that the natural world (*NW*) which forms the context of human and machine intelligence is a dual: one aspect of it is the *physical* world (*PW*), and the other is the *abstract* world (*AW*), where *intelligence* (αI) plays a central role in the transformation between information (*I*), *matter* (*M*), and *energy* (*E*). In the IME-I model as shown in Figure 1, αI plays an irreplaceable role in the transformation between information, matter, and energy, as well as different forms of internal information and knowledge. Typical paradigms of αI are natural intelligence, artificial intelligence, machinable intelligence, and computational intelligence, as well as their hybrid forms. The studies in CI and αI lay a theoretical foundation toward revealing the basic mechanisms of different forms of intelligence. As a result, cognitive computers may be developed, which are characterized as knowledge processors beyond those of data processors in conventional computing.

The Layered Reference Model of the Brain (LRMB)

The Layered Reference Model of the Brain (Wang et al., 2006) is developed to explain the fundamental cognitive mechanisms and processes of natural intelligence. Because a variety of life functions and cognitive processes have been identified in CI, psychology, cognitive science, brain science, and neurophilosophy, there is a need to organize all the recurrent cognitive processes in an integrated and coherent framework. The LRMB model encompasses 43 cognitive processes at seven layers known as the *sensation, memory, perception, action, metacognitive, metainference,* and *higher cognitive layers* from the bottom-up as shown in Figure 2.

LRMB explains the functional mechanisms and cognitive processes of the natural and artificial brains with the interactive processes at the seven layers (Wang et al., 2006). LRMB elicits the core and highly repetitive recurrent cognitive processes from a huge variety of life functions, which may shed light on the study of the fundamental mechanisms and interactions of complicated mental processes as well as of cognitive systems, particularly the relationships and interactions between the inherited and the acquired life functions at the subconscious and conscious layers.

Figure 1. The IME-I model and roles of abstract intelligence

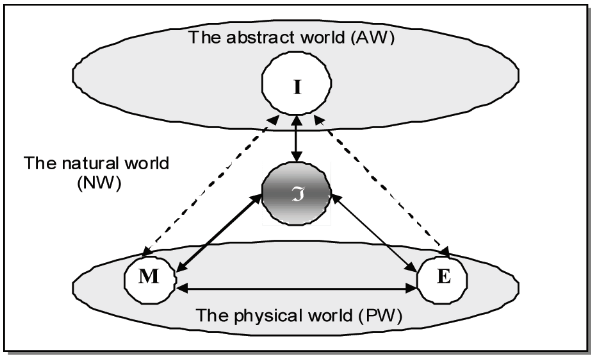
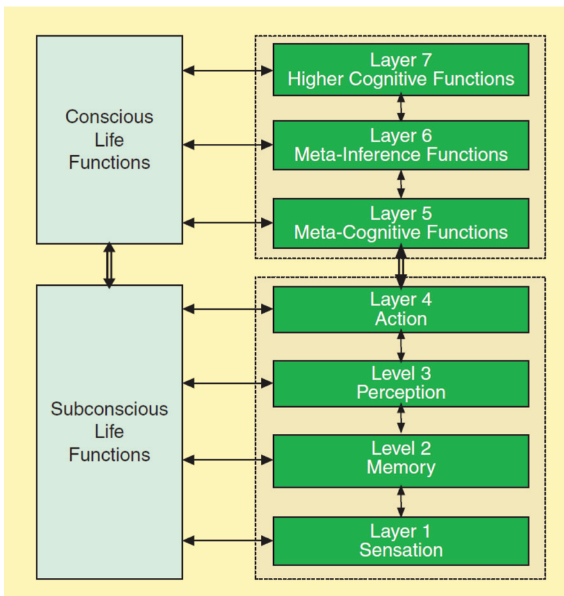


Figure 2. The layered reference model of the brain



Denotational Mathematics (DM)

The needs for complex and long-series of causal inferences in cognitive computing, αI, computational intelligence, software engineering, and knowledge engineering have led to new forms of mathematics collectively known as denotational mathematics (Wang, 2002b, 2007a, 2008a, 2008b, 2008c, 2008d, 2009c, 2009d, 2009e, 2010b, 2011, in press; Wang, Zadeh, & Yao, 2009). *Denotational Mathematics (DM)* is a category of expressive mathematical structures that deals with high-level mathematical entities beyond numbers and sets, such as abstract objects, complex relations, perceptual information, abstract concepts, knowledge, intelligent behaviors, behavioral processes, and systems (Wang, 2008a, 2009c, 2010b).

It is recognized that the maturity of any scientific discipline is characterized by the maturity of its mathematical (meta-methodological) means, because the nature of mathematics is a generic meta-methodological science (Wang, 2008a). In recognizing mathematics as the *metamethodology* of all sciences and engineering disciplines, a set of DMs have been created and applied in CI, αI, AI, CC, CogC, soft computing, computational intelligence, and computational linguistics. Typical paradigms of DM are such as *concept algebra* (Wang, 2008b; Wang, Widrow et al., 2011), *system algebra* (Wang, 2008c; Wang, Zadeh, & Yao, 2009), *real-time process algebra* (Wang, 2002b, 2007a, 2008d), *granular algebra* (Wang, 2009e), *visual semantic algebra* (Wang, 2009d), and *inference algebra* (Wang, 2011, in press). DM provides a coherent set of contemporary mathematical means and explicit expressive power for cognitive informatics, cognitive computing, artificial intelligence and computational intelligence.

Formal Knowledge Representation and Cognitive Learning Systems

An internal knowledge representing theory known as the *Object-Attribute-Relation* (OAR) model is proposed by Wang in 2007, which reveals the logical foundation of concepts and their attributes based on physiological and biological observations. The *OAR* model explains the mechanism of long-term memory (LTM) of the brain. It can be described as a triple (*O, A, R*), where *O* is a finite set of objects identified by unique symbolic names; *A* is a finite set of attributes for characterizing the objects; and *R* is a set of relations between an object and other objects or their attributes.

The OAR model explains the logic structure and configurations of knowledge based on physiological observations (Wang, 2007b). According to the OAR model, the mechanism and result of learning are the updating of the entire OAR in LTM, which can be formally modeled by a compositional operation (â) between the existing OAR and the newly created sub-*OAR* (sOAR), i.e.: *OAR'* = *OAR* â *sOAR* (Wang, 2008b; Wang, Tian, & Hu, 2011).

A Cognitive Learning Engine (CLE) (Tian et al., 2011), known as the "CPU" of CogCs, is under developing in the Cognitive Informatics and Cognitive Computing Lab on the basis of concept algebra (Wang, 2008b), which implements the basic and advanced cognitive computational operations of concepts and knowledge for CogCs. The work in this area may also lead to a fundamental solution to computational linguistics, computing with natural language (CNL), and computing with words (CWW) (Zadeh, 1965, 1975, 1999, 2008; Wang, 2010a, 2010c, 2010d).

Because CI and CC provide a common and general platform for the next generation of cognitive computing, a wide range of applications of CI, αI, CC, CogC, and DM are expected toward the implementation of highly intelligent machinable thought such as formal inference, symbolic reasoning, problem solving, decision making, cognitive knowledge representation, semantic searching, and autonomous learning. Some expected innovations that will be enabled by CI and CC are as follows, *inter alia*: a) A *reasoning machine* for complex and long-series of inferences, problem solving, and decision making beyond traditional logic and if-then-rule based technologies; b) An *autonomous learning system* for cognitive knowledge acquisition and processing; c) A novel *search engine* for providing comprehendable and formulated knowledge via the Internet; d) A *cognitive medical diagnosis system* supporting evidence-based medical care and clinical practices; e) A *cognitive computing node* for the next generation of the intelligent Internet; and f) A *cognitive processor* for cognitive robots (Wang, 2010e) and cognitive agents (Wang, 2009f).

3. PSYCHOLOGICALLY REALISTIC COGNITIVE COMPUTING BEYOND 2011

Language's recent evolutionary origin suggests that the computational machinery underlying syntax arose via the introduction of a single, simple, combinatorial operation. Further, the relation of a simple combinatorial syntax to the sensory-motor and thought systems reveals language to be asymmetric in design: while it precisely matches the representations required for inner mental thought, acting as the "glue" that binds together other internal cognitive and sensory modalities, at the same time it poses computational difficulties for externalization, that is, parsing and speech or signed production. Despite this mismatch, language syntax leads directly to the rich cognitive array that marks us as a symbolic species, including mathematics, music, and much more (Berwick, 2011).

Engineers have long appreciated the wisdom of the approach known as "KISS" – short for "Keep it Simple Stupid." But what about cognitive computing? Recent years have seen the rise of ever-more sophisticated and computationally intensive statistical models drawn from the analysis of biostatistics and the social sciences, now extended to the domain of human cognition. In particular, these models have recently been applied to human language acquisition, with the claim that they overcome previously insurmountable obstacles. However, there are two problems with these methods. First, they require computational resources well beyond the known bounds available to children. Second, one can show that far simpler models suffice to solve the same learning problems. In the domain of language acquisition at least, the KISS approach still prevails.

4. NEW VISION FOR THE WORLD OF WIRELESS COMMUNICATIONS ENABLED WITH COGNITION

During the past 10 years or so, much has been written on the application of human cognition in a variety of diverse fields. This new multidisciplinary subject is called Cognitive Systems. From an engineering perspective, Cognitive Systems may be categorized into three broadly defined classes: a) Cognitive dynamic systems (Haykin, 2011); b) Cognitive informatics (Wang, 2002a, 2003a, 2006, 2007b, 2007d, 2009a, 2009b; Wang & Kinsner, 2006; Wang & Wang, 2006; Wang, Zhang, & Kinsner, 2010; Wang, Kinsner, & Zhang, 2009; Wang, Kinsner et al., 2009); c) Cognitive computing (Wang, 2006, 2009b, 2009c, 2010a; Wang, Zhang, & Kinsner, 2010; Wang, Widrow et al., 2011; Modha et al., 2011);

In this section, I will discuss the four principles of cognition inspired by the human brain: perception-action cycle, memory, attention, and intelligence. In applying cognition to wireless communications, the current status of traditional cognitive radio is: i) spectrum sensing: the multitaper method, ii) transmit-power control: Nash equilibrium based on iterative water-filling, and iii) dynamic spectrum management: brain-inspired allocation of underutilized subbands of the radio spectrum in a multi-user network (Haykin, 2011). In my view, beyond traditional cognitive radio, new vision for the world of wireless communications includes: i) principle of cognition, ii) Femtocells: improved indoor reception, higher data rate, lower power consumption, and benefits to network providers. In developing cognitive Femtocell networks, the requirements are scalability, stability and heterogeneous coexistence community, and the tools and solutions are self-organized dynamic spectrum management, transmit-power control, spectrum identification and synchronization.

5. GRANULAR COMPUTING AND COGNITIVE INFORMATICS

As lucidly emphasized in Wang, Kinsner et al. (2009), Cognitive informatics is a transdisciplinary enquiry of cognitive and information sciences that brings together the mechanisms of information processing and processes of the brain and natural intelligence along with their engineering applications. Some interesting linkages between Cognitive Informatics and cyberntics are drawn in Wang, Kinsner, and Zhang (2009). An effective human – system interaction is one of the essential facets that becomes visible here especially in the context of applications. Information granules along with their numerous ways of formalization give rise to the discipline of Granular Computing (Bargiela & Pedrycz, 2003, 2008, 2009). In a nutshell, Granular Computing delivers a cohesive framework supporting a formation of information granules (as well as their ensuing hierarchical structures) and facilitating their processing. We elaborate on important facets of Granular Computing, which are also essential to Cognitive Informatics. This concerns a hierarchy of information granules, which contributes to a formation of a suitable cognitive perspective. Human centricity of Granular Computing is supported by a variety of formal ways in which information granules are represented, say fuzzy sets or rough sets. Tradeoffs between precision (and associated processing overhead) and interpretability of constructs of Granular Computing are formed by invoking a suitable level within the hierarchy of information granules.

6. DEALING WITH EMERGENT COGNITIVE SYSTEMS

Many developments of the last century focused on modeling of adaptation and adaptive systems. The focus in this century appears to have been shifting towards cognition and cognitive dynamical systems with emergence. Although cognitive dynamical systems are always adaptive to various conditions in the environment where they operate, adaptive systems of the past have not been cognitive.

The evolving formulation of cognitive informatics (CI) (Kinsner, 2007a, 2007b, 2009; Wang, 2002a, 2003a, 2007b; Wang, Widrow et al., 2011) has been an important step in bringing the diverse areas of science, engineering, and technology required to develop such cognitive computing (CogC) and cognitive systems. Cognitive computing focuses on the development a coherent, unified, universal, and system-based models inspired by the mind's nonlinear and evolutionary capabilities (Wang, 2009b; Wang, Zhang, & Kinsner, 2010; Modha et al., 2011). The intent of CogC is that by combining neuroscience, intelligent signal processing, supercomputing, nanotechnology and other non-standard technological developments, some insight into the brain's core algorithms might be possible.

Current examples of various cognitive systems include autonomic computing, memetic computing, cognitive radio, cognitive radar, cognitive robots, cognitive networks, cognitive computers, cognitive cars, cognitive factories, as well as brain-machine interfaces for physically-impaired persons, and cognitive binaural hearing instruments. The increasing interest in this area may be due to the recognition that perfect solutions to large-scale scientific and engineering problems may not be feasible, and we should seek the best solution for the task at hand. The "best" means suboptimal and the most reliable (robust) solution, given not only limited resources (financial and environmental) but also incomplete knowledge of the problem and partial observability of the environment. Many exciting new theoretical, computational and technological accomplishments have been described in recent literature.

The challenges in the evolving cognitive systems can be grouped into several categories: (a) theoretical, (b) technological, and (c) sociological. The first group of theoretical issues include modelling, reformulation of information and entropy, multi-scale measures and metrics, and management of uncertainty. Modelling of cognitive systems requires radically new approaches. *Reductionism* has dominated our scientific worldview for the last 350 years, since the times of Descartes, Galileo, Newton, and Laplace. In that approach, all reality can be understood in terms of particles (or strings) in motion. However, in this nonlinear (Enns, 2010) unfolding emergent universe with agency, meaning, values and purpose, we cannot predict all that will happen. Since cognitive systems rely on perceiving the world by agents, learning from it, remembering and developing the experience of self-awareness, feelings, intentions, and deciding how to control not only tasks but also communication with other agents, and to create new ideas, CI cannot rely on the reductionist approach of describing nature. In fact, CI tries to expand the modeling in order to deal with the emergent universe where no laws of physics are violated, and yet ceaseless unforeseeable creativity arises and surrounds us all the time. This new approach requires many new ideas to be developed, including reformulation of the concept of cognitive information, entropy, and associated measures, as well as management of uncertainty, and new forms of cognitive computing.

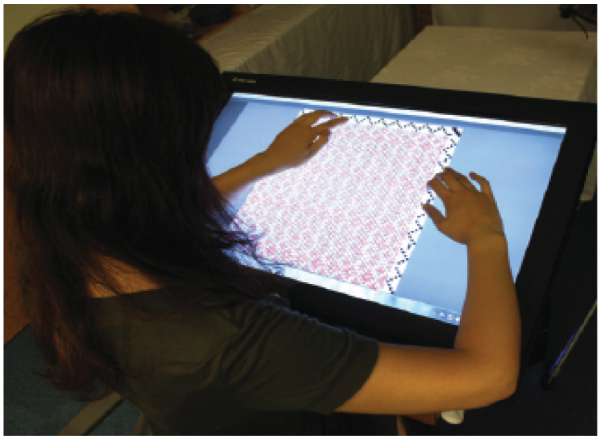
As we have seen over the last decade, cognitive informatics is multidisciplinary, and requires cooperation between many subjects, including sciences (e.g., cognitive science, computer science, evolutionary computing, granular computing, multi-criteria decision making, multi-objective evolutionary optimization, game theory, crisp and fuzzy sets, mathematics, physics, chemistry, biology, psychology, humanities, and social sciences), as well as engineering and technology (computer, electrical, mechanical, information theory, control theory, intelligent signal processing, neural networks, learning machines, sensor networks, wireless communications, and computer networks). Many of the new algorithms replace the conventional concepts of second order statistics (covariance, L2 distances, and correlation functions) with scalars and functions based on information theoretic underpinnings (such as entropy, mutual information and correntropy) defined not only on a single scale, but also on multiple scales. A serious challenge is the modeling and measuring of complexity of complex dynamical system (Kinsner, 2010). The continuing progress in the field may lead to some useful solutions to pressing problems.

7. COGNITIVE TEXTURE: A UNIFIED MULTI-SENSORY FEEDBACK FRAMEWORK

The human brain has an uncanny capacity to assimilate, integrate and fuse the multiple modalities from our visual, auditory, tactile, taste and olfactory sensors. The multi-sensory feedback modalities could be attributed to the perception of the change of environmental conditions. Observers often associate these changes to textures. Often, one can relate taste to texture, background sound to texture, as well as visual and tactile feedback as textures. The fusion of multi-sensory feedback seems to take the form of multi-dimensional textures. For example, tactile feedback is often correlated to visual perception of a surface. The two modalities can enforce each other into a richer form of multi-dimensional texture. We refer to these multi-sensory textures as CogTex, or Cognitive Texture. In its simplest form, CogTex relates any two or more channels of sensory feedback into a multi-dimensional cognitive texture. Multi-dimensional cognitive textures, specifically, visual, auditory and tactile, have recently become increasingly important in user interfaces through multi-touch visual displays. Here we will look at a few applications that are currently on a fast growing curve.

The world is now officially in a multi-touch, multitasking, multi-streaming mode. The number of *Apps* on the iPhone/iPad and Android systems is literally on an exponential growing curve.

Figure 3. Native multi-touch system for weaving design of virtual fabric



Software development for both iPhone OS and Android are in the hundreds. Developers are porting all the conceivable tools to tablets and smart phones. The latest entry into the frenzy, Nokia X7, possibly signals the capitulation of traditional PC/Laptop operating environments as the world converges onto the fastest growing computational platforms of all times as shown in Figure 3.

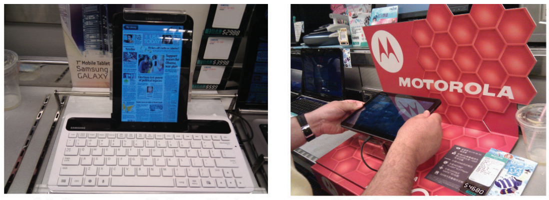
One of the latest contenders to the iPad2 generation, the Samsung's Galaxy pad 10.1 (or Galaxy 2) has made its debut at electronic shows and it is ready for launch. What is really interesting about the race is that despite the similar form factors and expected performance measurements, the tablet enthusiasts are looking for attributes that have not been considered in traditional computational technology before, especially portable ones. These are touch, feel, color and sound. More specifically, the devices are scrutinized in much more detail at a level of cognitive texture or CogTex for short.

The manifestation for human computer interaction has now taken another dimension in the tactile feel, image manipulation and the accompanying embedded sound feedback (Brooks et al., 2008; Cai & Baciu, 2011; Chen & Pappas, 2005; He & Pappas, 2010; Pappas et al., 2009). That is, all our sensory preceptors (minus one: olfactory), tactile, visual, auditory, are directly engaged in information processing (Rolls, 2005, 2008a, 2008b). However, these are currently very difficult modes to measure. For example, in video comparisons between iPad2 and Galaxy 10.1, the comments refer to the fact that the iPad2 "feels smoother" and the colors are "softer." The touch response is "less jerky" and "more fluid."

COGTEX: Cognitive Texture Modeling

Both these devices are state of the art multitouch tablet machines, but hardly anyone is paying attention to the IO throughput (other than video streaming), or the CPU, or GPU performance. The category of interest is now "texture" and not just "image texture" but also tactile, haptic (force feedback), and auditory. We have now transcended into a new era of cognitive texture information processing. Some of the not so new problems that we are fast converging to are taking a new flavor. Among these we can identify the following:

Figure 4. Dual touch tablets on exponential growth



(a) Samsung Galaxy Pad (b) Motorola XOOM

1. Cognitive processing under multimodal sensory feedback;
2. Balancing the load between feedback response (visual, tactile, auditory) and contextual processing;
3. Predictive cognitive behavior in the new multi-touch, multi-sensory environments.

An interesting question that arises from the above is under what conditions a common ground could be established for studying the cognitive interactions between these (at least) three modes and the brain. The answer could be found in the realm of "textures", or more appropriately "cognitive textures" or CogTex.

Based on preliminary studies (Bargiela & Pedrycz, 2009; Liang et al., 2010; Zhang et al., 2010; Zheng et al., 2010) that we are undergoing with digitizing textile materials, the iTextile project in the GAMA Lab at the Hong Kong Polytechnic University, Figure 4, we find that the CogTex platform could potentially unify the multimodal sensory feedback for cognitive processes. Supplemented by a theoretical behavior model such as cognitive algebra (Wang, 2003b, 2003c, 2008b) it can lead to a unifying theory of multi-modal cognitive sensory information processing.

8. BOUNDED RATIONALITY AND INCONSISTENCY IN COGNITIVE COMPUTING SYSTEMS

Cognitive computing systems are systems of bounded rationality. Toward the goal of building bounded rational cognitive computing systems, a whole host of human cognitive skills and abilities should be brought to bear. In this section, we call for attention on the interplay between inconsistency and bounded rationality, and emphasize on incorporating into the cognitive computing systems the human cognitive capability in handling inconsistency.

The theory of *bounded rationality*, developed by Simon (1982), underpins human intelligent behaviors. When engaged in problem solving, human beings' decision-making process is confined by the following constraints: the knowledge or information they possess, the cognitive limitations they have, and the time limit within which a decision needs to be made (Russell & Norvig, 2010). As a result, the human decision-making process in practice really consists in a search through a finite number of options, the fewer the better. People tend to identify with sub-goals rather than with global aims, exploit pre-existing structures or regularities in the environment, apply approximate or heuristic approaches to problems, and be content with good enough solutions.

In a nutshell, practical decision-making process is not a perfect rational process of finding an optimal solution (a solution that maximizes the expected utility) given the information available from the environment. Agents of bounded rationality exhibit *satisfying*, rather than optimizing, behavior: (1) seeking satisfactory solutions rather than optimal ones; (2) adopting simplified

Table 1. Heuristics

	Consistent	Inconsistent
Rational	RAC	RINC
Irrational	IRRAC	IRRINC

choices; (3) deliberating only long enough; and (4) relying on heuristic approaches rather than rigid rule of optimization.

To a large extent, building cognitive computing systems amounts to developing systems that possess bounded rationality. Toward the goal of bounded rational cognitive computing systems, a whole host of human cognitive skills and abilities should be brought to bear. In this section, we call for attention on the interplay between inconsistency and bounded rationality, and emphasize on incorporating into the cognitive computing systems the human cognitive capability in handling inconsistency.

Inconsistency is an important phenomenon that exists ubiquitously in human behaviors and in various aspects of real life (Gotesky, 1968). Inconsistent phenomena manifest themselves in data, information, knowledge, meta-knowledge, and expertise. Inconsistent or conflicting assumptions, beliefs, evidences, or options can serve as important heuristics in the decision-making process of a bounded rational agent (Zhang, 2011; Zhang & Lu, 2011). Using the consistency-rationality dichotomy, we can categorize heuristics as shown in Table 1.

Of particular interest is the category of *RINC* (inconsistent but rational heuristics), which can be of more powerful tools in the decision-making process.

9. COGNITIVE INFORMATICS TOWARDS 2031

Cognitive Informatics (CI) has been based on many disciplines, for example computer science, cognitive science and information sciences. CI has both scientific and engineering goals: (a) to understand and explain "intelligent" behavior living organisms, and (b) to develop systems that have some form of "intelligence".

CI consists of a multitude of techniques, theories, systems and applications. Some of the theories use numeric or sub-symbolic representations and often use vector-space models. Although they have been applied in a number of domains, they have certain inherent limitations due to their vector-space representations. On the other hand, other theories operate in the symbolic domain and these have been also applied in many applications. However, the emergence of symbols is not "natural" in these theories when we consider inputs from the real world through various sensors. Thus, it is clear that there is a lack of integrative and unified theory of cognition and intelligence that is applicable across various aspects and levels of cognition and intelligence.

Ideally, a unified theory of CI should be developed that will be able to explain various sensory perceptions, reasoning, intuition and all other intelligent processes. The technologies and systems based on such a theory would be applicable to construct systems applicable to all these domains. These systems would also exhibit some fundamental features of evolution in nature. Further, we believe that since biological systems embody a marked degree of parallel and distributed functioning, the CI architectures and/or their implementations should also embody some forms of intrinsic parallel and distributed computing. We hope that by 2031 we will have such a unified theory.

10. COMPUTATIONAL INTELLIGENCE IN BIOMETRIC

The area of computational intelligence in general and cognitive informatics in particular has experienced tremendous growth in the past decade. Research on neural networks, evolutionary computing, fuzzy logic, intelligent design and decision-making has influenced, in turn, growth in numerous application areas, such as pattern recognition, image processing, and biometric authentication. Biometric research specifically is one of the most dynamic areas which benefitted from such developments, which recently has displayed a gamut of broader links to other fields of sciences. Among those are visualization, robotics, multi-dimensional data analysis, computational geometry, computer graphics, e-learning, data fusion and data synthesis. The topic of this talk is reviewing state-of-the-art in multi-modal data fusion and neural networks and its recent connections to advanced biometric research. Application examples in this area demonstrate high potentials of this research symbiosis.

11. CONCLUSION

This paper has summarized nine position statements presented in the plenary panel of IEEE ICCI*CC'11 on *Cognitive Informatics in Year 10 and Beyond* contributed by invited panelists who are part of the world's renowned researchers and scholars in the field of cognitive informatics and cognitive computing. Cognitive Informatics (CI) has been described as a transdisciplinary enquiry of computer science, information sciences, cognitive science, and intelligence science that investigates into the internal information processing mechanisms and processes of the brain and natural intelligence, as well as their engineering applications in cognitive computing. Cognitive Computing (CC) has been recognized as an emerging paradigm of intelligent computing methodologies and systems that implements computational intelligence by autonomous inferences and perceptions mimicking the mechanisms of the brain. It has been elaborated that the theoretical foundations underpinning cognitive computing and cognitive computers (CogC) are cognitive informatics – the science of cognitive and intelligent information and knowledge processing.

A series of fundamental breakthroughs have been recognized and a wide range of applications has been developed in cognitive informatics and cognitive computing in the last decade. The representative paradigms and technologies developed in cognitive informatics and cognitive computing have been recognized as prototypes of cognitive computers, cognitive systems, cognitive knowledge bases, cognitive robots, cognitive learning engines, and autonomous inference systems and frameworks.

REFERENCES

Baciu, G., Yao, Y., Wang, Y., Zadeh, L. A., Chan, K., & Kinsner, W. (Eds.). (2009, June). *Proceedings of the 8th IEEE International Conference on Cognitive Informatics*. Washington, DC: IEEE Computer Society.

Bargiela, A., & Pedrycz, W. (2003). *Granular computing: An introduction*. Dordrecht, The Netherlands: Kluwer Academic.

Bargiela, A., & Pedrycz, W. (2008). Toward a theory of granular computing for human-centered information processing. *IEEE Transactions on Fuzzy Systems*, *16*(2), 320–330. doi:10.1109/TFUZZ.2007.905912

Bargiela, A., & Pedrycz, W. (Eds.). (2009). *Human-centric information processing through granular modelling*. Heidelberg, Germany: Springer-Verlag. doi:10.1007/978-3-540-92916-1

Bell, D. A. (1953). *Information theory*. London, UK: Pitman.

Berwick, R. C. (2011, August). Keynote: Songs to syntax: Cognition, combinatorial computation, and the origin of language. In *Proceedings of the 10th IEEE International Conference on Cognitive Informatics and Cognitive Computing*, Banff, AB, Canada (p. 1). Washington, DC: IEEE Computer Society.

Brooks, A. C., Zhao, X., & Pappas, T. N. (2008). Structural similarity quality metrics in a coding context: Exploring the space of realistic distortions. *IEEE Transactions on Image Processing*, 1261–1273. doi:10.1109/TIP.2008.926161

Cai, Y., & Baciu, G. (2011, June). Detection of repetitive patterns in near regular texture images. In *Proceedings of the 10th IEEE Conference on Perception and Visual Signal Analysis*, Ithaca, NY (pp. 60-65). Washington, DC: IEEE Computer Society.

Chan, C., Kinsner, W., Wang, Y., & Miller, D. M. (Eds.). (2004, August). *Proceedings of the 3rd IEEE International Conference on Cognitive Informatics*. Washington, DC: IEEE Computer Society.

Chen, J., Pappas, T. N., Mojsilovic, A., & Rogowitz, B. E. (2002). Adaptive image segmentation based on color and texture. In *Proceedings of the IEEE International Conference on Information Processing* (Vol. 3, pp. 777-780). Washington, DC: IEEE Computer Society.

Chen, J., Pappas, T. N., Mojsilovic, A., & Rogowitz, B. E. (2005). Adaptive perceptual color-texture image segmentation. *IEEE Transactions on Image Processing*, 1524–1536. doi:10.1109/TIP.2005.852204

Enns, R. H. (2010). *It's a nonlinear world*. New York, NY: Springer.

Goldman, S. (1953). *Information theory*. Upper Saddle River, NJ: Prentice Hall.

Gotesky, R. (1968). The uses of inconsistency. *Philosophy and Phenomenological Research*, *28*(4), 471–500. doi:10.2307/2105687

Haykin, S. (2011, August). Keynote: Cognitive dynamic systems: An integrative field that will be a hallmark of the 21st century. In *Proceedings of the 10th IEEE International Conference on Cognitive Informatics and Cognitive Computing*, Banff, AB, Canada (p. 2). Washington, DC: IEEE Computer Society.

He, L., & Pappas, T. N. (2010, September). An adaptive clustering and chrominance-based merging approach for image segmentation and abstraction. In *Proceedings of the IEEE 17th International Conference on Image Processing*, Hong Kong (pp. 241-244). Washington, DC: IEEE Computer Society.

Kinsner, W. (2007a). A unified approach to fractal dimensions. *International Journal of Cognitive Informatics and Natural Intelligence*, *1*(4), 26–46. doi:10.4018/jcini.2007100103

Kinsner, W. (2007b). Towards cognitive machines: Multiscale measures and analysis. *International Journal of Cognitive Informatics and Natural Intelligence*, *1*(1), 28–38. doi:10.4018/jcini.2007010102

Kinsner, W. (2009). Challenges in the design of adaptive, intelligent and cognitive systems. *International Journal of Software Science and Computational Intelligence*, *1*(3), 16–35. doi:10.4018/jssci.2009070102

Kinsner, W. (2010). System complexity and its measures: How complex is complex . In Wang, Y., Zhang, D., & Kinsner, W. (Eds.), *Advances in cognitive informatics and cognitive computing* (*Vol. 323*, pp. 265–295). Berlin, Germany: Springer-Verlag. doi:10.1007/978-3-642-16083-7_14

Kinsner, W. (2011, August). Keynote: It's time for multiscale analysis and synthesis in cognitive systems. In *Proceedings of the 10th IEEE International Conference on Cognitive Informatics and Cognitive Computing*, Banff, AB, Canada (pp. 7-10). Washington, DC: IEEE Computer Society.

Kinsner, W., Zhang, D., Wang, Y., & Tsai, J. (Eds.). (2005, August). *Proceedings of the 4th IEEE International Conference on Cognitive Informatics*. Washington, DC: IEEE Computer Society.

Liang, S., Chan, E., Baciu, G., & Li, R. (2010, July). Cognitive garment design interface using user behavior tree model. In *Proceedings of the 9th IEEE International Conference on Cognitive Informatics*, Beijing, China (pp. 496-500). Washington, DC: IEEE Computer Society.

Modha, D. S., Ananthanarayanan, R., Esser, S. K., Ndirango, A., Sherbondy, A. J., & Singh, R. (2011). Cognitive computing. *Communications of the ACM*, *54*(8), 62–71. doi:10.1145/1978542.1978559

Pappas, T. N., Tartter, V. C., Seward, A. G., Genzer, B., Gourgey, K., & Kretzshmar, I. (2009). Perceptual dimensions for a dynamic tactile display, human vision and electronic imaging. *Proceedings of the Society for Photo-Instrumentation Engineers*, 7240.

Patel, D., Patel, S., & Wang, Y. (Eds.). (2003, August). *Proceedings of the 2nd IEEE International Conference on Cognitive Informatics*. Washington, DC: IEEE Computer Society.

Pedrycz, W. (2011, August). Keynote: Human centricity and perception-based perspective of architectures of granular computing. In *Proceedings of the 10th IEEE International Conference on Cognitive Informatics and Cognitive Computing*, Banff, AB, Canada (p. 3). Washington, DC: IEEE Computer Society.

Pescovitz, D. (2002). Autonomic computing: Helping computers help themselves. *IEEE Spectrum*, *39*(9), 49–53. doi:10.1109/MSPEC.2002.1030968

Rolls, E. T. (2005). *Emotion explained*. Oxford, UK: Oxford University Press. doi:10.1093/acprof:oso/9780198570035.001.0001

Rolls, E. T. (2008a). *Memory, attention, and decision-making: A unifying computational neuroscience approach*. Oxford, UK: Oxford University Press.

Rolls, E. T. (2008b). The affective and cognitive processing of touch, oral texture, and temperature. *Journal of Neuroscience and Biobehavioral Reviews*, *34*, 237–245. doi:10.1016/j.neubiorev.2008.03.010

Russell, S., & Norvig, P. (2010). *Artificial intelligence: A modern approach*. Upper Saddle River, NJ: Prentice Hall.

Shannon, C. E. (1948). A mathematical theory of communication. *The Bell System Technical Journal*, *27*, 379–423, 623–656.

Shannon, C. E., & Weaver, W. (1949). *The mathematical theory of communication*. Urbana, IL: Illinois University Press.

Simon, H. A. (1982). *Models of bounded rationality*. Cambridge, MA: MIT Press.

Sun, F., Wang, Y., Lu, J., Zhang, B., Kinsner, W., & Zadeh, L. A. (Eds.). (2010, July). *Proceedings of the 9th IEEE International Conference on Cognitive Informatics*, Beijing, China. Washington, DC: IEEE Computer Society.

Tian, Y., Wang, Y., Gavrilova, M., & Rehe, G. (2011). A formal knowledge representation system for the cognitive learning engine. *International Journal of Software Science and Computational Intelligence*, *3*(4).

Wang, Y. (2002a, August). Keynote: On cognitive informatics. In *Proceedings of the 1st IEEE International Conference on Cognitive Informatics*, Calgary, AB, Canada (pp. 34-42). Washington, DC: IEEE Computer Society.

Wang, Y. (2002b). The Real-Time Process Algebra (RTPA). *Annals of Software Engineering*, *14*, 235–274. doi:10.1023/A:1020561826073

Wang, Y. (2003a). On cognitive informatics. *Brain and Mind: A Transdisciplinary Journal of Neuroscience and Neurophilosophy, 4*(2), 151-167.

Wang, Y. (2003b). Cognitive informatics: A new transdisciplinary research filed. *Brain and Mind*, *4*(2), 115–127. doi:10.1023/A:1025419826662

Wang, Y. (2003c). Using process algebra to describe human and software behavior. *Brain and Mind*, *4*(2), 199–213. doi:10.1023/A:1025457612549

Wang, Y. (2006, July). Keynote: Cognitive informatics - Towards the future generation computers that think and feel. In *Proceedings of the 5th IEEE International Conference on Cognitive Informatics*, Beijing, China (pp. 3-7). Washington, DC: IEEE Computer Society.

Wang, Y. (2007a). *Software engineering foundations: A software science perspective* (Vol. 2). Boca Raton, FL: Auerbach.

Wang, Y. (2007b). The theoretical framework of cognitive informatics. *International Journal of Cognitive Informatics and Natural Intelligence*, *1*(1), 1–27. doi:10.4018/jcini.2007010101

Wang, Y. (2007c). The OAR model of neural informatics for internal knowledge representation in the brain. *International Journal of Cognitive Informatics and Natural Intelligence*, *1*(3), 64–75. doi:10.4018/jcini.2007070105

Wang, Y. (2007d). Towards theoretical foundations of autonomic computing. *International Journal of Cognitive Informatics and Natural Intelligence*, *1*(3), 1–16. doi:10.4018/jcini.2007070101

Wang, Y. (2008a). On contemporary denotational mathematics for computational intelligence. *Transactions of Computational Science*, *2*, 6–29. doi:10.1007/978-3-540-87563-5_2

Wang, Y. (2008b). On concept algebra: A denotational mathematical structure for knowledge and software modeling. *International Journal of Cognitive Informatics and Natural Intelligence*, *2*(2), 1–19. doi:10.4018/jcini.2008040101

Wang, Y. (2008c). On system algebra: A denotational mathematical structure for abstract system modeling. *International Journal of Cognitive Informatics and Natural Intelligence*, *2*(2), 20–42. doi:10.4018/jcini.2008040102

Wang, Y. (2008d). RTPA: A denotational mathematics for manipulating intelligent and computational behaviors. *International Journal of Cognitive Informatics and Natural Intelligence*, *2*(2), 44–62. doi:10.4018/jcini.2008040103

Wang, Y. (2009a). On abstract intelligence: Toward a unified theory of natural, artificial, machinable, and computational intelligence. *International Journal of Software Science and Computational Intelligence*, *1*(1), 1–18. doi:10.4018/jssci.2009010101

Wang, Y. (2009b). On cognitive computing. *International Journal of Software Science and Computational Intelligence*, *1*(3), 1–15. doi:10.4018/jssci.2009070101

Wang, Y. (2009c). Paradigms of denotational mathematics for cognitive informatics and cognitive computing. *Fundamenta Informaticae*, *90*(3), 282–303.

Wang, Y. (2009d). On Visual Semantic Algebra (VSA): A denotational mathematical structure for modeling and manipulating visual objects and patterns. *International Journal of Software Science and Computational Intelligence*, *1*(4), 1–15. doi:10.4018/jssci.2009062501

Wang, Y. (2009e, June). Granular algebra for modeling granular systems and granular computing. In *Proceedings of the 8th IEEE International Conference on Cognitive Informatics*, Hong Kong (pp. 145-154). Washington, DC: IEEE Computer Society.

Wang, Y. (2009f). A cognitive informatics reference model of Autonomous Agent Systems (AAS). *International Journal of Cognitive Informatics and Natural Intelligence*, *3*(1), 1–16. doi:10.4018/jcini.2009010101

Wang, Y. (2010a, July). Keynote: Cognitive computing and World Wide Wisdom (WWW+). In *Proceedings of the 9th IEEE International Conference on Cognitive Informatics*, Beijing, China. Washington, DC: IEEE Computer Society.

Wang, Y. (2010b, August). Keynote: Cognitive informatics and denotational mathematics means for brain informatics. In *Proceedings of the 1st International Conference on Brain Informatics*, Toronto, ON, Canada.

Wang, Y. (2010c). On concept algebra for Computing with Words (CWW). *International Journal of Semantic Computing*, *4*(3), 331–356. doi:10.1142/S1793351X10001061

Wang, Y. (2010d). On formal and cognitive semantics for semantic computing. *International Journal of Semantic Computing*, *4*(2), 203–237. doi:10.1142/S1793351X10000833

Wang, Y. (2010e). Cognitive robots: A reference model towards intelligent authentication. *IEEE Robotics and Automation*, *17*(4), 54–62. doi:10.1109/MRA.2010.938842

Wang, Y. (2011). Inference Algebra (IA): A denotational mathematics for cognitive computing and machine reasoning (I). *International Journal of Cognitive Informatics and Natural Intelligence*, *5*(4).

Wang, Y. (in press). Inference Algebra (IA): A denotational mathematics for cognitive computing and machine reasoning (II). *International Journal of Cognitive Informatics and Natural Intelligence, 6*(1).

Wang, Y., Baciu, G., Yao, Y., Kinsner, W., Chan, K., & Zhang, B. (2010). Perspectives on cognitive informatics and cognitive computing. *International Journal of Cognitive Informatics and Natural Intelligence*, *4*(1), 1–29. doi:10.4018/jcini.2010010101

Wang, Y., Celikyilmaz, A., Kinsner, W., Pedrycz, W., Leung, H., & Zadeh, L. A. (Eds.). (2011, August). *Proceedings of the 10th IEEE International Conference on Cognitive Informatics and Cognitive Computing*, Banff, AB, Canada. Washington, DC: IEEE Computer Society.

Wang, Y., Johnston, R., & Smith, M. (Eds.). (2002, August). *Proceedings of the 1st IEEE International Conference on Cognitive Informatics*, Calgary, AB, Canada. Washington, DC: IEEE Computer Society.

Wang, Y., & Kinsner, W. (2006). Recent advances in cognitive informatics. *IEEE Transactions on Systems, Man and Cybernetics. Part C, Applications and Reviews*, *36*(2), 121–123. doi:10.1109/TSMCC.2006.871120

Wang, Y., Kinsner, W., Anderson, J. A., Zhang, D., Yao, Y., & Sheu, P. (2009). A doctrine of cognitive informatics. *Fundamenta Informaticae*, *90*(3), 203–228.

Wang, Y., Kinsner, W., & Zhang, D. (2009). Contemporary cybernetics and its faces of cognitive informatics and computational intelligence. *IEEE Transactions on System, Man, and Cybernetics . Part B*, *39*(4), 823–833.

Wang, Y., Tian, Y., & Hu, K. (2011, August). The operational semantics of concept algebra for cognitive computing and machine learning. *Proceedings of the 10th IEEE International Conference on Cognitive Informatics and Cognitive Computing*, Banff, AB, Canada. Washington, DC: IEEE Computer Society.

Wang, Y., & Wang, Y. (2006). Cognitive informatics models of the brain. *IEEE Transactions on Systems, Man and Cybernetics. Part C, Applications and Reviews*, *36*(2), 203–207. doi:10.1109/TSMCC.2006.871151

Wang, Y., Wang, Y., Patel, S., & Patel, D. (2006). A Layered Reference Model of the Brain (LRMB). *IEEE Transactions on Systems, Man, and Cybernetics . Part C*, *36*(2), 124–133.

Wang, Y., Widrow, B., Zhang, B., Kinsner, W., Sugawara, K., & Sun, F. (2011). Perspectives on the field of cognitive informatics and its future development. *International Journal of Cognitive Informatics and Natural Intelligence*, *5*(1), 1–17. doi:10.4018/jcini.2011010101

Wang, Y., Zadeh, L. A., & Yao, Y. (2009). On the system algebra foundations for granular computing. *International Journal of Software Science and Computational Intelligence*, *1*(1), 64–86. doi:10.4018/jssci.2009010105

Wang, Y., Zhang, D., & Kinsner, W. (Eds.). (2010). *Advances in cognitive informatics and cognitive computing*. Berlin, Germany: Springer-Verlag.

Wang, Y., Zhang, D., Latombe, J.-C., & Kinsner, W. (Eds.). (2008, August). *Proceedings of the 7th IEEE International Conference on Cognitive Informatics*, Stanford, CA. Washington, DC: IEEE Computer Society.

Yao, Y. Y., Shi, Z., Wang, Y., & Kinsner, W. (Eds.). (2006, July). *Proceedings of the 5th IEEE International Conference on Cognitive Informatics*, Beijing, China. Washington, DC: IEEE Computer Society.

Zadeh, L. A. (1965). Fuzzy sets and systems . In Fox, J. (Ed.), *Systems theory* (pp. 29–37). Brooklyn, NY: Polytechnic Press.

Zadeh, L. A. (1975). Fuzzy logic and approximate reasoning. *Syntheses*, *30*, 407–428. doi:10.1007/BF00485052

Zadeh, L. A. (1999). From computing with numbers to computing with words – from manipulation of measurements to manipulation of perception. *IEEE Transactions on Circuits and Systems I*, *45*(1), 105–119. doi:10.1109/81.739259

Zadeh, L. A. (2008, August). Toward human level machine intelligence – Is it achievable? In *Proceedings of the 7th IEEE International Conference on Cognitive Informatics*, Stanford, CA (p. 1). Washington, DC: IEEE Computer Society.

Zhang, D. (2011). Inconsistency-induced heuristics for problem solving. In *Proceedings of the 23rd International Conference on Software Engineering and Knowledge Engineering*, Miami, FL (pp. 137-142).

Zhang, D., & Lu, M. (2011, August). Inconsistency-induced learning: A step toward perpetual learners. *Proceedings of the 10th IEEE International Conference on Cognitive Informatics*, Banff, AB, Canada. Washington, DC: IEEE Computer Society.

Zhang, D., Wang, Y., & Kinsner, W. (Eds.). (2007, August). *Proceedings of the 6th IEEE International Conference on Cognitive Informatics*, Lake Tahoe, CA. Washington, DC: IEEE Computer Society.

Zhang, J., Baciu, G., Liang, S., & Liang, C. (2010, November). A creative try: Composing weaving patterns by playing on a multi-input device. In *Proceedings of the 17th ACM Symposium on Virtual Reality Software and Technology* (pp. 127-130).

Zheng, D., Baciu, G., & Hu, J. (2010). Weave pattern accurate indexing and classification using entropy-based computing. *International Journal of Cognitive Informatics and Natural Intelligence*, *4*(4), 76–92. doi:10.4018/jcini.2010100106

Yingxu Wang is professor of cognitive informatics, cognitive computing, and software engineering, President of International Institute of Cognitive Informatics and Cognitive Computing (IICICC), and Director of the Cognitive Informatics and Cognitive Computing Lab at the University of Calgary. He is a Fellow of WIF, a P.Eng of Canada, a Senior Member of IEEE and ACM, and a member of ISO/IEC JTC1 and the Canadian Advisory Committee (CAC) for ISO. He received a PhD in Software Engineering from the Nottingham Trent University, UK, and a BSc in Electrical Engineering from Shanghai Tiedao University. He has industrial experience since 1972 and has been a full professor since 1994. He was a visiting professor on sabbatical leaves in the Computing Laboratory at Oxford University in 1995, Dept. of Computer Science at Stanford University in 2008, and the Berkeley Initiative in Soft Computing (BISC) Lab at University of California, Berkeley in 2008, respectively. He is the founder and steering committee chair of the annual IEEE International Conference on Cognitive Informatics (ICCI). He is founding Editor-in-Chief of International Journal of Cognitive Informatics and Natural Intelligence *(IJCINI), founding Editor-in-Chief of* International Journal of Software Science and Computational Intelligence *(IJSSCI), Associate Editor of* IEEE Trans on System, Man, and Cybernetics (Part A)*, associate Editor-in-Chief of* Journal of Advanced Mathematics and Applications*, and Editor-in-Chief of* CRC Book Series in Software Engineering. *Dr. Wang is the initiator of several cutting-edge research fields or subject areas such as cognitive informatics, abstract intelligence, cognitive computing, cognitive computers, denotational mathematics (i.e., concept algebra, inference algebra, system algebra, real-time process algebra, granular algebra, and visual semantic algebra), software science (on unified mathematical models and laws of software, cognitive complexity of software, and automatic code generators, coordinative work organization theory, built-in tests (BITs), and deductive semantics of languages), the layered reference model of the brain (LRMB), the mathematical model of consciousness, and the reference model of cognitive robots. He has published over 110 peer reviewed journal papers, 220+ peer reviewed full conference papers, and 16 books in cognitive informatics, software engineering, and computational intelligence. He is the recipient of dozens international awards on academic leadership, outstanding contributions, research achievement, best papers, and teaching in the last three decades.*

Robert C. Berwick is Professor of Computational Linguistics in the Department of Electrical Engineering and Computer Science and the Department of Brain and Cognitive Sciences at the Massachusetts Institute of Technology. Professor Berwick received his A.B. degree from Harvard University in Applied Mathematics and his S.M. and PhD degrees from the Massachusetts Institute of Technology in Computer Science in Artificial Intelligence. Since then he has been a member of the MIT faculty, and is currently co-Director of the MIT Center for Biological and Computational Learning. He is the recipient of a Guggenheim Award, and the author of 7 books and many articles in the area of natural language processing, complexity theory, language acquisition, and the biology and evolution of language. His latest book, to be published by Oxford University Press, is Rich Grammars from Poor Inputs.

Simon Haykin is professor of electrical and computer engineering, FIEEE. FRSC, Distinguished University Professor. He is director of the Cognitive Systems Lab in Dept. of Electrical and Computer Engineering at McMaster University, Canada. Prof. Haykin is a pioneer of cognitive radio/radar and adaptive signal processing, as well as an expert in cognitive systems and communication/information systems.

Witold Pedrycz is Professor and Canada Research Chair (CRC - Computational Intelligence) in the Department of Electrical and Computer Engineering, University of Alberta, Edmonton, Canada. He is also with the Systems Research Institute of the Polish Academy of Sciences, Warsaw, Poland. In 2009 Dr. Pedrycz was elected a foreign member of the Polish Academy of Sciences. He main research directions involve Computational Intelligence, fuzzy modeling and Granular Computing, knowledge discovery and data mining, fuzzy control, pattern recognition, knowledge-based neural networks, relational computing, and Software Engineering. He has published numerous papers in this area. He is also an author of 14 research monographs covering various aspects of Computational Intelligence and Software Engineering. Witold Pedrycz has been a member of numerous program committees of IEEE conferences in the area of fuzzy sets and neurocomputing. Dr. Pedrycz is intensively involved in editorial activities. He is an Editor-in-Chief of Information Sciences *and Editor-in-Chief of* IEEE Transactions on Systems, Man, and Cybernetics - Part A. *He currently serves as an Associate Editor of* IEEE Transactions on Fuzzy Systems *and is a member of a number of editorial boards of other international journals. In 2007 he received a prestigious Norbert Wiener award from the IEEE Systems, Man, and Cybernetics Council. He is a recipient of the IEEE Canada Computer Engineering Medal 2008. In 2009 he has received a Cajastur Prize for Soft Computing from the European Centre for Soft Computing for "pioneering and multifaceted contributions to Granular Computing".*

Witold Kinsner is Professor and Associate Head of the Department of Electrical and Computer Engineering, University of Manitoba, Winnipeg, Canada. He is also Affiliate Professor at the Institute of Industrial Mathematical Sciences, Winnipeg, and Adjunct Scientist at the Telecommunications Research Laboratories (TRLabs), Winnipeg. He obtained his PhD in electrical and computer engineering from McMaster University, Hamilton, and was Assistant Professor in Electrical Engineering at McGill University. He was a co-founder of the first Microelectronics Centre in Canada, and was its Director of Research from 1979 to 1987. His current research focuses on entropy-based multiscale complexity metrics for cognitive machines and systems. He has been involved in research on robust algorithms and software/hardware computing engines for real-time multimedia, using wavelets, fractals, chaos, emergent computation, genetic algorithms, rough sets, fuzzy logic, higher-order statistics, and neural networks. Applications included signal and data compression, signal enhancement, classification, segmentation, and feature extraction in various areas such as real-time speech compression for multimedia, wideband audio compression, aerial and space ortho image compression, severe weather classification from volumetric radar data, radio and power-line transient classification, image/video enhancement, and modelling of complex processes such as dielectric discharges. He is now the University Advisor for the Canadian Satellite Design Challenge University of Manitoba team consisting of over 80 students and 50 advisors (academic, aerospace, industrial, business, and military). His motivation for engaging in projects related to new system architectures in space is that they require not only autonomous, autonomic and intelligent systems, but also cognitive systems to succeed.

Du Zhang received his PhD degree in Computer Science from the University of Illinois. He is a Professor of the Computer Science Department at California State University, Sacramento. His current research interests include: knowledge inconsistency, machine learning in software engineering, knowledge-based systems and multi-agent systems. He has authored or coauthored over 150 publications in journals, conference proceedings, and book chapters, in these and other areas. In addition, he has edited or co-edited eleven books and conference proceedings. He has served as the conference general chair, the program committee chair, a program committee co-chair, or a program vice chair/area chair for 24 international conferences, most of which are IEEE sponsored international conferences. Currently, he is an Associate Editor for International Journal on Artificial Intelligence Tools*, an Area Editor for* International Journal of Software Engineering and Knowledge Engineering*, a member of editorial board for* International Journal of Cognitive Informatics and Natural Intelligence*, a member of editorial board for* International Journal of Software Science and Computational Intelligence*, and a member of editorial board of the* Open Software Engineering Journal*. In addition, he has served as a guest editor for special issues of* International Journal of Software Engineering and Knowledge Engineering, International Journal on Artificial Intelligence Tools, Software Quality Journal, IEEE Transactions on SMC-Part B, EATCS Fundamenta Informaticae, International Journal of Semantic Computing, International Journal of Cognitive Informatics and Natural Intelligence, *and* International Journal of Computer Applications in Technology. *Du Zhang is a senior member of IEEE and a senior member of ACM.*

George Baciu holds a PhD degree in Engineering and a B.Math degree in Computer Science and Applied Mathematics from the University of Waterloo. Currently, he is a professor in the Department of Computing at The Hong Kong Polytechnic University. His research interests are computer graphics, image processing, user interfaces, motion tracking and information retrieval.

Virendrakumar C. Bhavsar is professor of computer science, Director of Advanced Computational Research Lab, former dean of the faculty of computer science at University of New Brunswick, Canada. Dr. Bhavsar is expert in intelligent systems, bioinformatics, and parallel/distributed computing.

Marina Gavrilova is an Associate Professor and associate head of the Department of Computer Science, University of Calgary. Dr. Gavrilova's research interests include computational geometry, image processing, optimization, exact computation and computer modeling. Dr. Gavrilova is a founder of two innovative research labs, the SPARCS Laboratory for Spatial Analysis in Computational Sciences and the Biometric Technologies Laboratory. Her publication list includes over 80 research papers, books and book chapters. Dr. Gavrilova is an Editor-in-Chief of Transactions on Computational Science, *Springer and serves on the Editorial Board for* International Journal of Computational Sciences and Engineering *and* Computer Graphics and CAD/CAM Journal. *She is an ACM, IEEE and Computer Society member.*