Preface

1. INTRODUCTION

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, 2003, 2006, 2007b, 2009a, 2009b; Wang and Kinsner, 2006; Wang and Wang, 2006; Wang and Chiew, 2010; Wang, Kinsner, and Zhang, 2009b; Wang et al., 2002, 2006, 2008, 2009b, 2009c; Baciu et al., 2009; Chan et al., 2004; Kinsner et al., 2005; Patel et al., 2003; Yao et al., 2006; Zhang et al., 2007; Sun et al., 2010). 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, 2003, 2007b, 2009a, 2010a, 2010c). The development and the cross fertilization among the aforementioned science and engineering disciplines have led to a whole range of extremely interesting new research areas 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.

Definition 1. *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.

The IEEE series of International Conferences on Cognitive Informatics (ICCI) has been established since 2002 (Wang, 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); and Tsinghua University, Beijing (ICCI'10) (Sun et al., 2010). Since its inception, ICCI 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.

This chapter explores the cutting-edge field of CI and its applications in cognitive computing. The theoretical framework of CI is described in Section 2 on the architecture of CI, the abstract intelligence theory of CI, and denotational mathematics for CI. Inspirations of CI to theories for cognitive computing and technologies for cognitive computers are presented in Sections 3. The relationship among abstract, natural, and artificial intelligence is formally elaborated in Section 4 where abstract intelligence provides a theoretical foundation for understanding other forms of natural and artificial intelligence. Applications of CI and cognitive computers are described in Section 5.

2. THE THEORETICAL FRAMEWORK OF COGNITIVE INFORMATICS

It is recognized that *information* is any property or attribute of the natural world that can be distinctly elicited, generally abstracted, quantitatively represented, and mentally processed. Information is the third essence of the natural world supplementing 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 theoretical framework of CI (Wang, 2007b) encompasses: a) fundamental theories of cognitive informatics; b) abstract intelligence; and c) denotational mathematics. An intensive review on *The Theoretical Framework of Cognitive Informatics* was presented in (Wang, 2007b), which provides a coherent summary of the latest advances in the transdisciplinary field of CI and an insightful perspective on its future development.

Fundamental Theories of CI: 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 decades. *Conventional information theories* (Shannon and Weaver, 1949; Bell, 1953; Goldman, 1953), particularly Shannon's information theory (Shannon, 1948) known as the first-generation informatics, study signals and channel behaviors based on statistics and probability theory. *Modern informatics* studies information as properties or attributes of the natural world that can be generally abstracted, quantitatively represented, and mentally processed. The first- and second-generation informatics put emphases on external information processing, which overlook the fundamental fact that human brains are the original sources and final destinations of information, and any information must be cognized by human beings before it is understood, comprehended, and consumed. This observation leads to the establishment of the third-generation informatics, a term coined by Wang in 2002 as cognitive informatics (CI) in the keynote in (Wang, 2002a), which 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.

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 and Wang, 2006), natural intelligence (Wang, 2007b), and neuroinformatics (Wang, 2007b). 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).

Abstract Intelligence (αI): The studies on 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 as shown in Fig. 1 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 Fig. 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.

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, 2008e, 2009d, 2010e; Wang, Zadeh and Yao, 2009).

Definition 2.*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.

It is recognized that the maturity of a 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, soft computing, computational intelligence, and computational linguistics. Typical paradigms of DM are such as *concept algebra* (Wang, 2008c), *system algebra* (Wang, 2008d; Wang, Zadeh and Yao, 2009), *real-time process algebra* (Wang, 2002b, 2007a, 2008b), *granular algebra* (Wang, 2009e), *visual semantic algebra* (Wang, 2009c), *inference algebra* (Wang, 2010a, 2010b), and fuzzy inferences (Zadeh, 1965, 1975, 2008). DM

Figure 1. The IME-I model and roles of abstract intelligence in CI
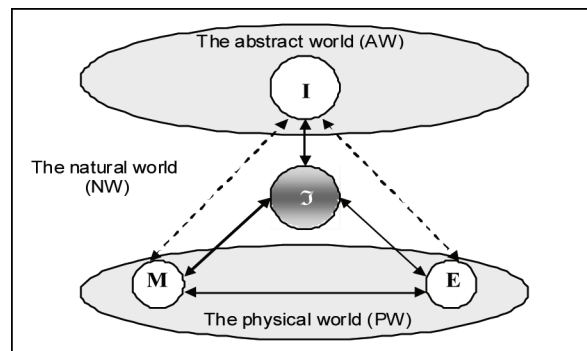
provides a coherent set of contemporary mathematical means and explicit expressive power for CI, αI, AI, and computational intelligence.

3. COGNITIVE COMPUTING AND COGNITIVE COMPUTERS

The term *computing* in a narrow sense is an application of computers to solve a given problem by imperative instructions; while in a broad sense, it is a process to implement the instructive intelligence by a system that transfers a set of given information or instructions into expected intelligent behaviors. The latest advances and engineering applications of CI have led to the emergence of cognitive computing and the development of cognitive computers that perceive, reason, and learn. *Cognitive Computing* is an emerging paradigm of intelligent computing methodologies and systems based on cognitive informatics that implements computational intelligence by autonomous inferences and perceptions mimicking the mechanisms of the brain (Wang, 2002a, 2007d, 2009b; Wang et al., 2010).

Definition 3. *Cognitive Computing* (CC) is a novel paradigm of intelligent computing methodologies and systems that implements computational intelligence by autonomous inferences and perceptions mimicking the mechanisms of the brain.

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 traditional and 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.

Definition 4. A *cognitive computer* (cC) is an intelligent computer for knowledge processing that perceive, learn, and reason.

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 to implement 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 mimicking the natural intelligence of the brain.

A cC is a type of intelligent computers that are capable of autonomous inference and learn. cCs are an emerging technology towards novel computer architectures and advanced intelligent computing behaviors for cognitive knowledge processing and autonomous learning based on contemporary denotational mathematics. cCs provide a general computing platform that extends computational intelligence from data/information processing to knowledge/intelligence processing. In seeking the contemporary mathematical means for cCs as well as for internal knowledge representation and manipulations, a set of denotational mathematics has been developed as described in Section 2. Denotational mathematics creates a coherent set of contemporary mathematical means and explicitly expressive power for rigorously modeling and implementing machine inference and learning processes for cCs.

The *essences* of computing are both its *data objects* and their predefined computational *operations*. From these facets, different computing paradigms may be comparatively analyzed as follows:

a. Conventional computers
   ◦ *Data objects*: abstract bits and structured data
   ◦ *Operations*: logic, arithmetic, and functions
b. Cognitive computers (cC)
   ◦ *Data objects*: words, concepts, syntax, and semantics
   ◦ *Basic operations*: syntactic analyses and semantic analyses
   ◦ *Advanced operations*: concept formulation, knowledge representation, comprehension, learning, inferences, and causal analyses

The above analyses indicate that cC is an important extension of conventional computing in both data objects modeling capabilities and their advanced operations at the abstract level of concept beyond bits. Therefore, cC is an intelligent knowledge processor that is much closer to the capability of human brains thinking at the level of concepts rather than bits. It is recognized that the basic unit of human knowledge in natural language representation is a concept rather than a word (Wang, 2008c, 2010d, 2010e), because the former conveys the structured semantics of a word with its intention (attributes), extension (objects), and relations to other concepts in the context of a knowledge network.

It is noteworthy that, although the semantics of words may be ambiguity, the semantics of concepts is always unique and precise in cC. For example, the word, "bank", is ambiguity because it may be a notion of a financial institution, a geographic location of raised ground of a river/lake, and/or a storage of something. However, the three individual concepts derived from bank, i.e., b_o = bank(organization), b_r = bank(river), and b_s = bank(storage), are precisely unique, which can be formally described in concept algebra (Wang, 2008c, 2010e) for cC as shown in Fig. 2. In the examples of concepts, a generic framework of a concept is represented by the following model known as an abstract concept c, i.e.:

$$c \triangleq (O, A, R^c, R^i, R^o) \tag{1}$$

where

- O is a nonempty set of objects of the concept, $O = \{o_1, o_2, ..., o_m\} \subseteq \mathrm{Þ}O$, where $\mathrm{Þ}O$ denotes a power set of abstract objects in the universal discourse U., $U = (O, A, R)$.
- A is a nonempty set of attributes, $A = \{a_1, a_2, ..., a_n\} \subseteq \mathrm{Þ}A$, where $\mathrm{Þ}A$ denotes a power set of attributes in U.
- $R^c = O \times A$ is a set of internal relations.
- $R^i \subseteq C' \times c$ is a set of input relations, where C' is a set of external concepts in U.
- $R^o \subseteq c \times C'$ is a set of output relations.

A set of denotational mathematics for cC and CC (Wang, 2002b, 2008b, 2008c, 2008d, 2009c, 2009d, 2009e; Wang et al., 2009a), particularly *concept algebra* (Wang, 2008b), has been developed by Wang during 2000 to in 2009. CA provides a set of 8 relational and 9 compositional operations for abstract concepts. A Cognitive Learning Engine (CLE) that serves as the "CPU" of cCs is under developing on the basis of concept algebra, which implements the basic and advanced cognitive computational operations of concepts and knowledge for cCs. 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) as Zadeh proposed (Zadeh, 1975, 2008).

Figure 2. Formal concepts modeled by concept algebra

$b_o\textbf{ST} \triangleq (A, O, R^c, R^i, R^o)$

$= (b_o\textbf{ST}.A = \{$organization, company, financial business, money, deposit, withdraw, invest, exchange$\}$,

$b_o\textbf{ST}.O = \{$international_bank, national_bank, local_bank, investment_bank, ATM$\}$

$b_o\textbf{ST}.R^c = O \times A$,

$b_o\textbf{ST}.R^i = \mathfrak{K} \times b_o\textbf{ST}$,

$b_o\textbf{ST}.R^o = b_o\textbf{ST} \times \mathfrak{K}$

)

$b_r\textbf{ST} \triangleq (A, O, R^c, R^i, R^o)$

$= (b_r\textbf{ST}.A = \{$sides of a river, raised ground, a pile of earth, location$\}$,

$b_r\textbf{ST}.O = \{$river_bank, lake_bank, canal_bank$\}$

$b_r\textbf{ST}.R^c = O \times A$,

$b_r\textbf{ST}.R^i = \mathfrak{K} \times b_r\textbf{ST}$,

$b_r\textbf{ST}.R^o = b_r\textbf{ST} \times \mathfrak{K}$

)

$b_s\textbf{ST} \triangleq (A, O, R^c, R^i, R^o)$

$= (b_s\textbf{ST}.A = \{$storage, container, place, organization$\}$,

$b_s\textbf{ST}.O = \{$information_bank, resource_bank, blood_bank$\}$

$b_s\textbf{ST}.R^c = O \times A$,

$b_s\textbf{ST}.R^i = \mathfrak{K} \times b_s\textbf{ST}$,

$b_s\textbf{ST}.R^o = b_s\textbf{ST} \times \mathfrak{K}$

)

4. ABSTRACT INTELLIGENCE VS. ARTIFICIAL INTELLIGENCE

It is conventionally deemed that only mankind and advanced species possess intelligence. However, the development of computers, robots, software agents, and autonomous systems indicates that intelligence may also be created or embodied by machines and man-made systems. Therefore, it is one of the key objectives in cognitive informatics and intelligence science to seek a coherent theory for explaining the nature and mechanisms of both natural and artificial intelligence.

Definition 5. *Intelligence* is an ability to acquire and use knowledge and skills, or to inference in problem solving.

It is a profound human wonder on how conscious intelligence is generated as a highly complex cognitive state in human mind on the basis of biological and physiological structures. How natural intelligence functions logically and physiologically? How natural and artificial intelligence are converged on the basis of brain, software, and intelligence science?

Definition 6. *Abstract intelligence* is the general form of intelligence as an abstract mathematical model that transfers information into behaviors and knowledge.

Abstract intelligence is also a discipline of human enquiries.

Definition 7. The *discipline of abstract intelligence* (αI) studies the foundations of intelligence science focusing the core properties of intelligence as a natural mechanism that transfers information into behaviors and knowledge.

In the *narrow sense*, αI is a human or a system ability that transforms information into behaviors. While, in the *broad sense*, αI is any human or system ability that autonomously transfers the forms of abstract information between *data, information, knowledge,* and *behaviors* in the brain or systems.

The studies on αI form a field of enquiry for both natural and artificial intelligence at the reductive levels of neural, cognitive, functional, and logical from the bottom up (Wang, 2009a). The paradigms of αI are such as natural, artificial, machinable, and computational intelligence. With the clarification of the intension and extension of the concept of αI, its paradigms or concrete forms in the real-world can be derived as summarized in Table 1.

Definition 8. The *behavioral model* of αI, §αIST, is an abstract logical model denoted by a set of parallel processes that encompasses the *imperative* intelligence I_I, *autonomic* intelligence I_A, and *cognitive* intelligence I_C from the bottom-up, i.e.:

$$
\begin{aligned}
\S\alpha\mathbf{IST} \triangleq (\Im_I, \Im_A, \Im_C) & \\
= \{ \quad (B_e, B_t, B_{int}) \qquad\qquad & // \ I_I \text{ - Imperative intelligence} \\
|| (B_e, B_t, B_{int}, B_g, B_d) \qquad & // \ I_A \text{ - Autonomic intelligence} \\
|| (B_e, B_t, B_{int}, B_g, B_d, B_p, B_{inf}) \ \ & // \ I_C \text{ - Cognitive intelligence} \\
\} &
\end{aligned}
\tag{2}
$$

According to Definition 8, the relationship among the three forms of intelligence is as follows:

$$
\Im_I \subseteq \Im_A \subseteq \Im_C
\tag{3}
$$

Both Eqs. 2 and 3 indicate that any lower layer intelligence and behavior is a subset of those of a higher layer. In other words, any higher layer intelligence and behavior is a natural extension of those of lower layers.

Table 1. Taxonomy of Abstract Intelligence and Its Embodying Forms

No.	Form of intelligence	Embodying means	Paradigms
1	Natural intelligence (NI)	Naturally grown biological and physiological organisms	Human brains and brains of other well developed species
2	Artificial intelligence (AI)	Cognitively-inspired artificial models and man-made systems	Intelligent systems, knowledge systems, decision-making systems, and distributed agent systems
3	Machinable intelligence (MI)	Complex machine and wired systems	Computers, robots, autonomic circuits, neural networks, and autonomic mechanical machines
4	Computational intelligence (CoI)	Computational methodologies and software systems	Expert systems, fuzzy systems, autonomous computing, intelligent agent systems, genetic/evolutionary systems, and autonomous learning systems

It is noteworthy that all paradigms of αI share the same cognitive informatics foundation as described in the following theorems, because they are an artificial or machine implementation or embodiment of αI.

Theorem 1. The *compatible intelligent capability* state that *natural intelligence* (NI), *artificial intelligence* (AI), *machinable intelligence* (MI), and *computational intelligence* (CoI), are compatible by sharing the same mechanisms of αI, i.e.:

$$CoI \cong MI \cong AI \cong NI \cong \alpha I \qquad (4)$$

On the basis of Theorem 1, the differences between NI, AI, MI, and CoI are only distinguishable by: (a) The means of their implementation; and (b) The extent of their intelligent capability.

Corollary 1. The *inclusive intelligent capability* states that all real-world paradigms of intelligence are a subset of αI, i.e.:

$$CoI \subseteq MI \subseteq AI \subseteq NI \subseteq \alpha I \qquad (5)$$

Corollary 1 indicates that AI, CoI, and MI are dominated by NI and αI. Therefore, one should not expect a computer or a software system to solve a problem where human cannot. In other words, no AI or computer systems may be designed and/or implemented for a given problem where there is no solution being known collectively by human beings as a whole. Further, Theorem 1 and Corollary 1 explain that the development and implementation of AI rely on the understanding of the mechanisms and laws of NI.

5. APPLICATIONS OF CI AND CC

The studies in CI and αI lay a theoretical foundation toward revealing the basic mechanisms of different forms of intelligence (Wang, 2010c). As a result, cognitive computers may be developed, which are characterized as a knowledge processor beyond those of data processors in conventional computing. Key applications in the above cutting-edge fields of CI and CC can be divided into two categories. The first category of applications uses informatics and computing techniques to investigate problems of intelligence science, cognitive science, and brain science, such as abstract intelligence, memory, learning, and reasoning. The second category of applications includes the areas that use cognitive informatics theories to investigate problems in informatics, computing, software engineering, knowledge engineering, and computational intelligence. CI focuses on the nature of information processing in the brain, such as information acquisition, representation, memory, retrieval, creation, and communication. Through the interdisciplinary approach and with the support of modern information and neuroscience technologies, mechanisms of the brain and the mind may be systematically explored based on the theories and cognitive models of CI.

Because CI and CCs provide a common and general platform for the next generation of cognitive computing, a wide range of applications of CI, αI, CC, 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 CCs are as follows, *inter alia*: a) An *inference machine* for complex and long-series of reasoning, 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 implementing cognitive robots and cognitive agents.

6. CONCLUSION

This chapter has summarized the latest development in cognitive informatics, abstract intelligence, denotational mathematics, cognitive computing, and cognitive computers. The theoretical framework of cognitive informatics and cognitive computing has been reviewed. The context and relations among the aforementioned fields have been elaborated. A set of applications in the cutting-edge areas has been reported.

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