Perspectives on the Field of Cognitive Informatics and its Future Development

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ABSTRACT

The contemporary wonder of sciences and engineering has recently refocused on the beginning point of: how the brain processes internal and external information autonomously and cognitively rather than imperatively like conventional computers. Cognitive Informatics (CI) is a transdisciplinary enquiry of computer science, information sciences, cognitive science, and intelligence science that investigates the internal information processing mechanisms and processes of the brain and natural intelligence, as well as their engineering applications in cognitive computing. This paper reports a set of eight position statements presented in the plenary panel of IEEE ICICI’10 on Cognitive Informatics and Its Future Development 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 Informatics, Computational Intelligence, Denotational Mathematics, Ebrain, Engineering Applications, Machinable Intelligence, Natural Intelligence

1. INTRODUCTION

Cognitive informatics is a transdisciplinary enquiry of computer science, information science, cognitive science, and intelligence science, which investigates into the internal information process-
ing mechanisms and processes of the brain and natural intelligence, as well as their engineering applications in cognitive computing (Wang, 2002a, 2003, 2006, 2007c, 2009c, 2009d; Wang & Kinsner, 2006; Wang & Wang, 2006; Wang & Chiew, 2010; Wang, Kinsner, & Zhang, 2009; Wang, Johnston, & Smith, 2002; Wang, Wang, Patel, & Patel, 2006; Wang, Zhang, Latombe, & Kinsner, 2008, Wang et al., 2009; 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). Cognitive informatics 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, 2007c, 2009c, 2010b, 2010d). 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 Cognitive informatics, which investigates the internal information processing mechanisms and processes of the natural intelligence – human brains and minds – and their engineering applications in computational intelligence. Cognitive informatics studies the natural intelligence and internal information processing mechanisms of the brain, as well as processes involved in perception and cognition. Cognitive informatics 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, 2002a). The inaugural ICCI event in 2002 was held at University of Calgary, Canada (ICCI’02) (Wang, Johnston, & Smith, 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, Zhang, Latombe, & Kinsner, 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.

The latest advances and engineering applications of CI have led to the emergence of cognitive computing (CC) and the development of cognitive computers that think, perceive, learn, and reason (Wang, 2006, 2009e, 2010a, 2010b; Wang et al., 2009; Wang, Kinsner, & Zhang, 2009). CI has also fundamentally contributed to autonomous agent systems (Wang, 2009a) and cognitive robots (Wang, 2010b). A wide range of applications of CI has been identified such as in the development of cognitive computers, cognitive robots, cognitive agent systems, cognitive search engines, cognitive learning systems, and artificial brains. The work in CI may also lead to a fundamental solution to computational linguistics, Computing with Natural Language (CNL), and Computing with Words (CWW) (Zedeck, 1975, 1999).

This paper is a summary of the position statements of panellists presented in the *Plenary Panel on Cognitive Informatics and Its Future Development* in IEEE ICCI 2010 at Tsinghua
University held in July 2010 (Sun et al., 2010). It is noteworthy that the individual statements and opinions included in this paper may not necessarily be shared by all panellists.

2. COGNITIVE INFORMATICS (CI): THE SCIENCE OF ABSTRACT INTELLIGENCE AND COGNITIVE COMPUTING

CI establishes a systematical framework for brain and computational intelligence studies as well as their applications at hierarchical levels known as the functional level, the mathematical (logical) level, the cognitive level, and the neural (physiological) level. Corresponding to the four reductive levels as shown in Figure 1, the theoretical framework of CI (Wang, 2007c) encompasses four main areas of basic and applied research on: a) Abstract intelligence: fundamental theories of natural intelligence; b) Denotational mathematics for modeling abstract intelligence; c) Cognitive models of the brain; d) Neural informatics; and e) Cognitive computing. These areas of CI are elaborated in the following subsections.

Abstract Intelligence (αI): The studies on αI form a human enquiry of both natural and artificial intelligence at the reductive neural, cognitive, logical, and functional levels from the bottom up (Wang, 2009c). The paradigms of αI are such as natural, artificial, machinable, and computational intelligence. The studies in CI and αI lay a theoretical foundation toward revealing the basic mechanisms of different forms of intelligence (Wang, 2010a). As a result, cognitive computers may be developed, which are characterized as knowledge processors beyond those of data processors in conventional computing.

Cognitive Models of the Brain: Fundamental theories developed in CI covers the Information-Matter-Energy (IME) model (Wang, 2007a), the Layered Reference Model of the Brain (LRMB) (Wang, Wang, Patel, & Patel, 2006), the Object-Attribute-Relation (OAR) model of information/knowledge representation in the brain (Wang, 2007c), the cognitive inform-

Figure 1. The architecture and theoretical framework of Cognitive Informatics (CI)
matics model of the brain (Wang, 2010b; Wang & Wang, 2006), and Natural Intelligence (NI) (Wang, 2007c). 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, Wang, Patel, & Patel, 2006).

**Neural Informatics (NeI):** Neural informatics is an emerging interdisciplinary enquiry of the biological and physiological representation of information and knowledge in the brain at the neuron level and their abstract mathematical models (Wang, 2007c). NeI is an important branch of cognitive informatics, which reduces cognitive informatics theories and the studies on the internal information processing mechanisms of the brain onto the neuron and physiological level. In neural informatics, memory is recognized as the foundation and platform of any natural or machine intelligence based on the OAR model (Wang, 2007b; Wang & Wang, 2006) of information/knowledge representation. The theories of neural informatics explain a number of important questions in the study of natural intelligence. Enlightening findings in neural informatics are such as (a) Long-Term Memory (LTM) establishment is a subconscious process; (b) The long-term memory is established during sleeping; (c) The major mechanism for LTM establishment is by sleeping; (d) The general acquisition cycle of LTM is equal to or longer than 24 hours; (e) The mechanism of LTM establishment is to update the entire memory of information represented as an OAR model in the brain (Wang, 2007b); and (f) Eye movement and dreams play an important role in LTM creation.

**Denotational Mathematics (DM):** 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). A number of DMs have been created and developed such as concept algebra (Wang, 2008b, 2010c), system algebra (Wang, 2008c; Wang, Zadeh, & Yao, 2009), real-time process algebra (RTPA) (Wang, 2002b, 2008d), granular algebra (Wang, 2010c), visual semantic algebra (VSA) (Wang, 2009e), and formal causal inference methodologies (Wang, in press). It is recognized that the maturity of a scientific discipline is characterized by the maturity of its mathematical (meta-methodological) means. DM provides a coherent set of contemporary mathematical means and explicit expressive power for CI, αI, NeI, CC, AI, and computational intelligence.

**Applications of CI, αI, NeI, and DM:** The key applications of the fundamental theories and technologies of CI can be divided into two categories. The first category of applications uses informatics and computing techniques to investigate intelligence science, cognitive science, and knowledge science problems, such as abstract intelligence, memory, learning, and reasoning. The second category 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 (Wang & Chiew, 2010) within the framework of CI.

A key and exiting application of CI is its inspiration to and theoretical preparation for cognitive computers (cCs), which is an intelligent computer for knowledge processing as that of a
conventional von Neumann computer for data processing. A cC is driven by a cognitive CPU with a cognitive learning engine and formal inference engine for intelligent operations on abstract concepts as the basic unit of human knowledge (Wang, 2009d, 2010c, 2010d). CCs are designed based on contemporary denotational mathematics (Wang, 2008a, 2009f), particularly concept algebra, as that of Boolean algebra for the conventional von Neumann architecture computers.

3. CI/CC AND COGNITIVE MEMORY

Cognitive computing is brain-like computing. Emulating mental processing is inherently difficult, since the overall working of the human brain is more or less unknown. Instead of trying to model the functioning of the entire brain, it is proposed that a portion be studied, an important portion, long-term memory. Without memory we can live, but we would not really exist as human beings.

Human memory is exceedingly complex. However, by observing our own behavior and that of fellow humans, electrical engineers can devise memory systems that exhibit human-like behavior. In my laboratory at Stanford University (Widrow & Aragon, 2010), we have constructed an elementary form of cognitive memory consisting of both software and hardware. We have used this memory to solve problems in the fields of pattern recognition, face recognition and control systems.

Taking inspiration from life experience, we have devised a new form of computer memory (Widrow & Aragon, 2010). Certain conjectures about human memory are keys to the central idea. We present the design of a practical and useful “cognitive” memory system. The new memory does not function like a computer memory where specific data is stored in specific numbered registers and retrieval is done by reading the contents of the specified memory register, or done by matching key words as with a document search. Incoming sensory data would be stored at the next available empty memory location, and indeed could be stored redundantly at several empty locations. The stored sensory data would neither have key words nor would it be located in known or specified memory locations. Retrieval would be initiated by a prompt signal from a current set of sensory inputs or patterns. The search would be done by a retrieval system that makes use of auto-associative artificial neural networks. A practical application of this cognitive memory system to human facial recognition has been implemented.

4. THE MULTIDISCIPLINARY RESEARCH FOR COGNITIVE COMPUTATION

Cognitive informatics should benefit from the multidisciplinary research among information science, cognitive science and brain science, etc. (Zhang, 2010). Taking computer vision as an example, human visual performances are much better than computer vision in many cases recently. Therefore, computer vision should learn something from the visual mechanism of human cognition in the brain.

As we known, the main approaches adopted in recent computer object recognition are statistics-based and data-driven. The objects (images) are represented in the data space composed by the computer’s robustly detectable features. These features are generally less meaningful, i.e., so called low-level features, such as colors, textures, etc. Due to the big gap between semantics and low level features, image recognition, classification, and etc. are difficult to implement in computer vision. But human brain processes visual information in the conceptual space where the semantically meaningful features are extracted such as line-segments, boundaries, shapes, etc. Therefore, there is no semantic gap in human visual information processing. In order to
endow computers with the human capacity, we need to learn from the human visual information processing mechanisms (Zhang, 2010).

In order to promote the multidisciplinary research, the Center for Neural and Cognitive Computation was established at Tsinghua University in 2009. It includes the fields of computational neuroscience, system neuroscience, information science, psychology, neural information, brain-computer interface, learning, and memory, etc.

5. EVOLUTION OF COGNITIVE DYNAMICAL SYSTEMS AND COGNITIVE INFORMATICS

Many developments of the last century focused on adaptation and adaptive systems. The focus in this century appears to be 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) (Wang, 2002a, 2003, 2007c; Wang & Kinsner, 2006; Wang, Kinsner, & Zhang, 2009; Wang, Zhang, & Tsumoto, 2009) has been an important step in bringing the diverse areas of science, engineering, and technology required to develop such cognitive systems. 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 phenomenal 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 at IEEE ICCI conferences and related journals.

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 includes modeling, reformulation of information and entropy, multiscale measures and metrics, and management of uncertainty. Modeling 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 unfolding emergent universe with agency, meaning, values and purpose, we cannot prestate or 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 only 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 (Wang, 2003, 2007c; Wang & Kinsner, 2006; Wang, Zhang, & Tsumoto, 2009), and requires cooperation between many subjects, including sciences (e.g., cognitive science, evolutionary computing,
granular computing, computer science, 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. Two recent special issues of the IEEE Proceedings are dedicated to cognitive systems with their practical perspectives (April 2009), and fundamental issues (May 2009).

6. COGNITIVE COMPUTING AND SYMBIOTIC COMPUTING

Cognitive Computing (CC) is an emerging paradigm of intelligent computing methodologies and systems based on cognitive informatics that implements computational intelligence by autonomous inferences and perception mimicking of the brain (Wang, 2009d; Wang et al., 2009). The Layered Reference Model of the Brain (LRMB) was proposed as a seven-layered model of the function layers of the brain for the fundamental cognitive mechanisms and processes of natural intelligence (Wang, Wang, Patel, & Patel, 2006).

Symbiotic Computing (SC) is a methodology based on cognitive computing, ubiquitous computing and agent-based computing to develop systems that have their significance of existence for serving humans, their goals of actions for obtaining the trust of them through their services, and their desire for growing up their capabilities to serve them, along with them through practice collaborating with them. The framework of SC is based on an agent framework that works on the Symbiotic-computing-based System Platform (SSP), which consists of partner tracking function, symbiotic zone control function, symbiotic zone sensing function and perception function corresponding to the low layers of the LRMB. The intelligent agents which work on the platform have functions of cognition corresponding to the upper layers of the LRMB and social knowledge to cooperate with humans and with other intelligent agents working on the platform and providing social norm, customs, conveniences and risks for humans.

The Symbiotic Zone (Symbiozone or SYZ) is a conceptual space surrounding a person with ubiquitous and wearable sensors and effectors in order for an intelligent agent called a Partner Agent (PA) to communicate with only person called a partner of the PA. The PA follows the partner by tracking him/her, finding sensors and effectors around him/her and making a network of the devices dynamically wherever possible. The partner can communicate with the PA when she/he wants and the PA gives advices if it considers that it should do it then for the partner.

The PA is an intelligent and complex software system based on a multi-agent system architecture, in which the following disciplines of behavior are implemented:

(1) Significance of existence to serve its partner
(2) Goals of action to serve its partner
(3) Desire of co-growing with its partner

In SYZ, a partner and a PA maintain close contact like the Licklinder’s view of Man-Computer symbiosis (Licklider, 1960) and promote mutual understanding to achieve the categories of (1) - (3). To do so in the SYZ, a PA has the following functions inside, (a) perceiving poses and actions of the partner, (b) perceiving surroundings of the partner, (c) acquiring partner’s requirements,
(d) understanding partner’s intension, (e) serving the partner based on the intension and requirements, (f) advising the partner against risky actions based on assessment function of actions of the partner from social point of view.

In order to assess actions of both a partner and its PA from the social point of view, a Group Agent (GA) cooperates with PAs for a group or a community, which supports group dynamics (Grundin, 2002) using the Social Informatics (Wang, Carley, Zeng, & Mao, 2007). The social informatics stored in a GA is acquired by mining information from Web and is learned through actions that a PA and a partner have made in the group. This SC project aims at developing cognitive systems which work in an area ranging from network systems to physical places where ubiquitous devices are embedded, working like the cognitive machine (Kinsner, 2002).

7. ROBOTICS AND COGNITIVE INFORMATION PROCESSING

As an ideal platform for research on cognitive information processing, robots have been paid strong attention for many years and many successful progresses have been achieved (Sun et al., 2010; Wang, 2010b). In the National Laboratory of Information Science and Technology (TNLIST) at Tsinghua University, the only state laboratory in the field of information sciences at the national level in China, various types of robots have been developed, such as mobile robots (also named as intelligent vehicles), flexible-link manipulators, space robots, unmanned aerial vehicles, soccer robots, and so on. Based on these well-equipped platforms, researchers in this laboratory have developed comprehensive theory and approaches for robot sensing and control. Many novel approaches are deeply rooted at cognitive informatics, such as fuzzy control, neural network control, path planning using genetic algorithms and estimation distributed algorithm, visual serving using cognitive approach, object tracking based on machine learning.

Recently, a more collaborative project is being conducted in TNLIST, which is supported by the National Science Foundation of China. This project aims at controlling a mobile robot using brain-computer-interface (BCI). The BCI signal processing module is provided by the Medical School of Tsinghua University. Researchers in TNLIST will develop more rich local environmental information to aid human for teleoperation of the remote mobile robots. This project integrates many research fields including robots, computer vision, and brain sciences. We hope the advanced studies reported above provide more insights of TNLIST towards the future development of cognitive informatics and its engineering applications.

8. CI/CC AND EVOLUTIONARY COMPUTATION

Evolutionary Computation (EC) (Weise, 2009) comprises all Monte Carlo metaheuristics which iteratively refine sets (populations) of multiple candidate solutions. Most EC approaches are either Swarm Intelligence (SI) methods or Evolutionary Algorithms (EAs). SI is inspired by fact that natural systems of many independent, simple agents (such as ants or birds) are of tenable to find pieces of food or shortest distance routes very efficiently. EAs, on the other hand, copy the behavior of natural evolution and treat candidate solutions as individuals which compete and reproduce in a virtual environment defined by the user-provided objective function(s). Generation after generation, these individuals adapt to the environment and thus, tend to become suitable solutions for the problem at hand.

Past: The roots of EC go back to the mid-1950s, where the biologist Barricelli (1954) began to apply computer-aided simulations in order to gain more insight into the natural evolution. Bremermann (1962) and Bledsoe (1961) were the first ones to use evolutionary approaches
for solving optimization problems. In the early 1980s Genetic Programming emerged as the youngest member of the EA family (1980). The most common SI methods followed in the 1990s (Dorigo et al., 1996; Eberhart & Kennedy, 1995).

Present: Evolutionary Computation now exists for almost 50 years. When taking a look on the current situation of this area, I get the impression that (1) countless algorithm variants and analyses have been published and EC became widely accepted in the research community. (2) Most of the evidence of the efficiency of EAs is based on experiments and empirical studies. Due to the many configuration parameters of EAs and the wide range of existing optimization problems, it is very hard to define meaningful boundaries for performance or required runtime. (3) A tendency towards hybridizing optimization techniques can be observed, resulting from this lack of knowledge about which algorithm is “good” for which problem. This trend began in the 1970s (Bosworth, 1972), lead to the development of Memetic Algorithms (Moscato, 1989), and now culminates in the emergence of portfolio methods (Peng et al., 2010), which choose the best methods from an algorithm portfolio during the actual process of solving a given problem. (4) Despite the available evidence for the high utility of EAs, practitioners who solve real-world optimization problems appear to often prefer traditional, exact methods. Large-scale problems, which these approaches cannot handle any more due to their computational complexity, are often approached manually instead of using meta-heuristics which could have provided much better solutions in shorter time (Weise et al., 2009). (5) The communication between researchers working on meta-heuristic optimization and those working on traditional, exact methods is low; both communities appear to be separated.

Future: My humble opinion about the future development in the EC area is that (1) in the next ten to twenty years, metaheuristic optimization should undergo a slow transition from a research area to a service. Virtually every decision or design task in engineering and business is an optimization problem. Yet currently, only the fewest of them are recognized as such and even fewer are actually solved using a suitable technique. More joint projects between research and economy targeting real-world applications are necessary to improve the awareness and trust of practitioners in EC. (2) EA research should thus focus on tasks which are interesting for practitioners, such as large-scale real-world problems (Weise et al., 2009), in order to become more attractive for them. (3) Up to date, in my opinion, no framework exists for analyzing EAs theoretically which provides results that are actually useful in practice. The development of a robust and simple analysis approach would be highly desirable since it would further increase the acceptance of EC. (4) A closer cooperation between the EC community and traditional/emerging areas, such as cognitive informatics (Wang, 2002a, 2007c) and cognitive computing (Wang, 2009d), should be pursued, since an exchange of ideas would be beneficial for both sides.

9. INCONSISTENCY, MEMORY, AND INCONSISTENCY-INDUCED LEARNING

The focus of this section of the position paper is on the interplay among inconsistency, long-term memory, and inconsistency-induced learning in a cognitive system. There are five conclusions that are summarized as follows.

Two important types of memories exist in a human memory model: short-term memory (STM) and long-term memory (LTM) (Wang, 2007b; Wang & Wang, 2006; Wang, Kinsner, & Zhang, 2009). STM is a working memory where reasoning takes place with activated beliefs.
The reasoning in STM results in actions taken that will affect a human being’s behavior. STM has limited storage capacity and duration. Activated beliefs in STM come from either sensory memory or LTM.

LTM, on the other hand, is where beliefs are retained for long-term purpose. In general, LTM does not have practical capacity limit and some information can be stored in LTM indefinitely (Cherniak, 1983). Beliefs in LTM do not have direct impact on a person’s behavior unless they are recalled or retrieved to STM. In traditional models, beliefs in LTM are referred to as “relatively inert” (Cherniak, 1983). Some recent constructive memory models regard beliefs in LTM not as completely inactive once retained, but as undergoing some sort of transformation after acquisition and before recall. According to (McGuire, 1960), beliefs in LTM are organized into various “compartments” in human thinking apparatus. Cognitions and beliefs that are not recalled or activated contemporaneously tend to be separated into different compartments (Cherniak, 1983).

LTM invariably contains inconsistent beliefs. There are several reasons for this. The vast number of beliefs a person possesses makes it a daunting and next to impossible task to keep track of inconsistent beliefs. The compartmentalized structure in LTM is such that logical relations and inconsistencies between beliefs in different compartments are far less likely to be identified than those of beliefs belonging to the same compartment. The following observation in (Shastri & Grannes, 1996) succinctly summarizes the phenomenon: “we often hold inconsistent beliefs in our long-term memory without being explicitly aware of such inconsistencies. But at the same time, we often recognize contradictions in our beliefs when we try to bring inconsistent knowledge to bear on a particular task.”

The second sentence of the aforementioned quote from (Shastri & Grannes, 1996) describes the fact that inconsistent beliefs in LTM manifest their influence on a person’s behavior through STM, because items from LTM cannot directly affect behavior, they have to be recalled or retrieved to STM to influence one’s behavior. In general, inconsistency detection is intractable (Johnson-Laird et al., 2004). Detecting inconsistencies in STM hinges on several conditions: the presence of a triggering event from sensory memory that causes additional beliefs to be recalled from LTM; efficient recall, and organization of compartmentalized beliefs in LTM. Failure of detecting inconsistency at STM may have detrimental or costly consequence.

To facilitate inconsistency detection process in a cognitive system, we propose to augment the constructive memory model by tagging potential inconsistent beliefs in LTM. The tagging approach relies on (1) obtaining a fixpoint representation for each compartment of beliefs (Zhang, 2005, 2007, 2008); (2) fusing fixpoints for individual compartments into one that allows us to establish relevant inter-compartment logical relations and inconsistencies between or among beliefs of different compartments; (3) tagging a set of beliefs that are conflicting with each other according to the nature of the inconsistency involved; and (3) organizing tags with regard to different types of inconsistency (Zhang, 2009). We call such a transformed LTM a tagged LTM, denoted as tLTM.

Assume that two beliefs \( P_i \) and \( P_k \) in tLTM belong to either the same compartment or two different compartments and that \( P_i \) and \( P_k \) are conflicting with each other. When recalling beliefs from tLTM into STM for a particular task at hand, even though one of \( P_i \) and \( P_k \), but not both contemporaneously, is in STM, the tag, say, \( P_i \) has would alert the detection mechanism at STM to ascertain if the reasoning and subsequent actions should proceed with tagged \( P_i \) in STM. This would help improve the inconsistency detection and subsequent handling process. Of course the upfront price we pay is the transformation of LTM into tLTM.

Finally, identified inconsistency at STM can serve as an impetus to belief revisions at LTM. As quoted in (Gotesky, 1968), Henri Poincare once said that contradiction is the prime stimulus
for scientific research. So to conclude, we would like to end with the follow slogan: inconsistency in LTM is a terrible thing to waste.

10. CONCLUSION

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. This paper summarizes the presentations of a set of eight position papers in the IEEE ICU’10 Panel on Cognitive Informatics and Its Future Development contributed from invited panelists who are part of the world’s preeminent researchers and scholars in the field of cognitive informatics and cognitive computing.

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