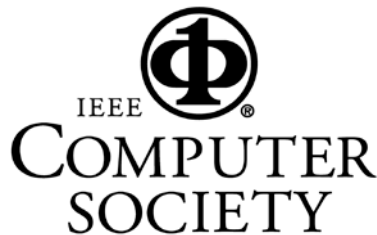


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9th IEEE International Conference on Cognitive Informatics (ICCI 2010)



清華大學

Tsinghua University

Tsinghua University

©2010 IEEE, ISBN 978-1-4244-8040-1

Edited by

July 7-9, 2010

<http://www.icci2010.edu.cn/>

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Perspectives on Cognitive Informatics and Its Future Development: Summary of Plenary Panel II of IEEE ICCI'10

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ABSTRACT

The contemporary wonder of sciences and engineering has recently refocused on the beginning point of them: how the brain processes internal and external information autonomously and cognitively rather than imperatively as those of conventional computers. 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. This paper reports a set of 9 position statements presented in the plenary panel of ICCI'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: *Cognitive informatics, cognitive computing, cognitive computers, abstract intelligence, natural intelligence, artificial intelligence, machinable intelligence, computational intelligence, denotational mathematics, concept algebra, system algebra, RTPA, visual semantic algebra, granular algebra, ICCI, eBrain, engineering applications*

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 [1, 3, 6, 12, 13, 18, 20, 21, 22, 23, 25]. CI is emerged and developed based on the multidisciplinary research in cognitive informatics, abstract

intelligence, and denotational mathematics since the inauguration of the 1st IEEE ICCI'02 [1].

The latest advances and engineering applications of CI have led to the emergence of *cognitive computing* and the development of *cognitive computers* that think, perceive, learn, and reason [4, 13, 15, 17, 18, 26]. CI has also fundamentally contributed to autonomous agent systems and cognitive robots. 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) [28, 29].

This joint paper reports a summary of the positions of panellists presented in the Plenary Panel on *Cognitive Informatics and Its Future Development* in ICCI 2010. Please note that the individual statements and opinions included in this paper may not necessarily be shared by all panellists.

2. Cognitive Informatics: The Science of Abstract Intelligence and Cognitive Computing

(Yingxu Wang)

The theoretical framework of CI [6] encompasses four main areas of basic and applied research such as: a) fundamental theories of natural intelligence; b) abstract intelligence; c) denotational mathematics; and d) cognitive computing. These areas of CI are elaborated in the following subsections.

The Theoretical Framework of CI: Fundamental theories developed in CI covers the Information-Matter-Energy (IME) model [5], the Layered Reference Model of the Brain (LRMB) [22], the Object-Attribute-Relation (OAR) model of information/knowledge representation in the brain [7], the

cognitive informatics model of the brain [17, 20], Natural Intelligence (NI) [6], and neuroinformatics [6]. 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 [22].

Abstract Intelligence (α I): The studies on α I form a human enquiry of both natural and artificial intelligence at the reductive levels of neural, cognitive, functional, and logical from the bottom up [12]. The paradigms of α I are such as natural, artificial, machinable, and computational intelligence. The studies in CI and α I lay a theoretical foundation toward revealing the basic mechanisms of different forms of intelligence [19]. 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): *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 [8]. A category of DMs have been created and developed such as concept algebra [9], system algebra [10, 24], real-time process algebra (RTPA) [2, 11], granular algebra [24], visual semantic algebra (VSA) [14], and formal causal inference methodologies. 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, α I, CC, AI, and computational intelligence.

Applications of CI, α I, 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 [27] 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. cCs are designed based on contemporary denotational mathematics [8, 16], particularly concept algebra, as that of Boolean algebra for the conventional von Neumann architecture computers.

3. CI/CC and Cognitive Memory (Bernard Widrow)

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, 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.

4. The Multidisciplinary Research for Cognitive Computation (Bo Zhang)

Cognitive informatics should benefit from the multidisciplinary research among information science, cognitive science and brain science, etc. 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 that 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.

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

5. Evolution of Cognitive Dynamical Systems and Cognitive Informatics *(Witold Kinsner)*

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) [3, 6, 21, 23, 25] 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 this conference 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 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 [3, 6, 21, 25], 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). Several new books on cognitive dynamical systems and computational intelligence have also been published.

6. Cognitive Computing and Symbiotic Computing *(Kenji Sugawara)*

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, Y. 2010). 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, Y., 2007).

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 Licklider's view of Man-Computer symbiosis (Licklider, J.C.R., 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 J., 2002) using the Social Informatics (Wang, F.Y., 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.

Our 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, W., 2007).

7. Robotics and Cognitive Information Processing

(Fuchun Sun)

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. In the National Lab. 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 from 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 Medical School of Tsinghua University. Researchers in TNLIST will develop more rich local environmental information to aid the 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

(Thomas Weise)

Evolutionary Computation (EC [1]) 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 [2] began to apply computer-aided simulations in order to gain more insight into the natural evolution. Bremermann [3] and Bledsoe [4] 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 [5]. The most common SI methods followed in the 1990s [6,7].

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 [8], lead to the development of Memetic Algorithms [9], and now culminates in the emergence of portfolio methods [10], 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 [11]. (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 [11], in order to become more attractive for them. (3) Up to date, in my opinion, there exists no framework 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 and cognitive computing, should be pursued, since an exchange of ideas would be beneficial for both sides.

9. Cognitive Informatics and Advanced Intelligence

(Yixin Zhong)

The terminology of “Advanced Intelligence” was formally proposed as a new direction, program and paradigm for Intelligence Science and Technology research in the years to come at the 2006 International Conference on Artificial Intelligence, which was jointly organized by the Chinese Association for Artificial Intelligence (CAAI), the American Association for Artificial Intelligence (AAAI) and the European Coordination for Artificial Intelligence (ECAI) for the celebration of the 50th anniversary of the birth of Artificial Intelligence.

The major features of Advanced Intelligence include: (1) it should have a unified approach to the intelligence research instead of three separated approaches as it was before; (2) it should have closely interaction with Natural Intelligence research instead of isolation as it had been before; and (3) it should make endeavor for integrative study on Consciousness, Emotion, Intelligence, and their interrelation instead of ignoring the other two as it was during the past years.

Apparently, the feature (1) is a reasonable requirement for any research area, the feature (2) is also a necessary requirement demanding the interaction among Intelligence, Cognition and Neurology, and the feature (3) is a common goal not only for the intelligence research but also for the research of Cognition and Neurology. The program on Advanced Intelligence is regarded as a new approach to AI studies from a historical point of view.

The study on Advanced Intelligence has made encouraging progress since 2006. The unified approach to intelligence research has been established as “the Approach of Intelligence Formation” which can be expressed as the Information Conversion that converse the information to Knowledge and further to Intelligence. The Information Conversion approach is also believed a powerful tool leading to the deep understanding of consciousness, emotion and cognition. It will, no doubt, be a promising approach to Advanced Intelligence and Cognitive Informatics [1, 3, 6, 25].

It is strongly believed that the study on Advanced Intelligence, particularly the study on integration of consciousness, emotion and intelligence would pave a good way to cognitive computing [4, 13]. Hence, the cooperation among Advanced Intelligence, Cognitive Informatics and Neurology is of extremely significance.

10. Inconsistency, Memory, and Inconsistency-Induced Learning (Du Zhang)

The focus of this 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). 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 [1]. 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" [1]. 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 [1]. According to [4], 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 [1].

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 [1]. The following observation in [5] 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 [5] 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 [3]. 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 [6-8]; (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 [9]. 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 [2], 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.

11. Conclusions

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 9 position papers in the ICCI'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.

On behalf of the IEEE ICCI Steering Committee, we would like to warm welcome all authors and participants of ICCI'10 to attend IEEE ICCI 2011, the 10th anniversary of the ICCI series, in Banff, AB, Canada during August 8-10, 2011, where ICCI has been inaugurated. Over the last decade, CI and CC have been established as an exciting research field, which has already created and attracted millions of entries over the Internet and related research communities. The theme of ICCI'11 will be on "*eBrain and Cognitive Computing*".

Therefore, from this event, the IEEE ICCI series will be extended to *International Conference on Cognitive Informatics and Cognitive Computing (ICCI*CC)* series in order to better identify and represent the discipline of CI and CC research as well as engineering and industrial applications. We look forward to meeting you again at “ICCI*CC 2010”!

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[Sections 1, 2, 5 and 9]

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@inproceedings{WWZKSSWZZ2010POCI AIFDSOPPI I O I I ,
 author = {Yingxu {Wang} and Bernard {Widrow} and Bo {Zhang} and
 Witold {Kinsner} and Kenji {Sugawara} and Fuchun {Sun} and
 Thomas {Weise} and Yixin {Zhong} and Du {Zhang}},
 title = {{Perspectives on Cognitive Informatics and Its Future Development:
 Summary of Plenary Panel II of IEEE ICCI'10}},
 Booktitle = {Proceedings of the 9th IEEE International Conference on Cognitive
 Informatics (ICCI'09)},
 Editor = {Fuchun {Sun} and Yingxu {Wang} and Jianhua {Lu} and Bo {Zhang} and
 Witold {Kinsner} and Lotfi A. {Zadeh}},
 publisher = {{IEEE Computer Society Press: {Los Alamitos, CA, USA}}},
 pages = {17--25},
 year = {2010},
 month = jul # {-7-9},
 location = {{Tsinghua University: {Beijing, China}}},
 abstract = {The contemporary wonder of sciences and engineering has recently
 refocused on the beginning point of them: how the brain processes
 internal and external information autonomously and cognitively rather
 than imperatively as those of conventional computers. 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. This paper reports a
 set of 9 position statements presented in the plenary panel of ICCI'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 = {EC, Evolutionary Computation, CI, Computational Intelligence,
 Cognitive informatics, cognitive computing, cognitive computers,
 abstract intelligence, natural intelligence, artificial intelligence,
 machinable intelligence, computational intelligence, denotational
 mathematics, concept algebra, system algebra, RTPA, visual semantic
 algebra, granular algebra, ICCI, eBrain, engineering
 applications},

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<http://www.it-weise.de/>



Published by the IEEE Computer Society
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10662 Los Vaqueros Circle
P.O. Box 3014
Los Alamitos, CA 90720-1314

ISBN: 978-1-4244-8040-1
IEEE Catalog Number: CFP10312-CDR

ISBN 978-1-4244-8040-1



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