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Preface: Cognitive Informatics, Cognitive Computing, and Their Denotational Mathematical Foundations (I)

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Abstract. *Cognitive Informatics* is a cutting-edge and multidisciplinary research area that tackles the fundamental problems shared by modern informatics, computing, software engineering, AI, cybernetics, cognitive science, neuropsychology, medical science, systems science, philosophy, linguistics, economics, management science, and life sciences. This editorial introduces the emerging field of cognitive informatics and its applications in cognitive computing, abstract intelligence, computational mathematics, and computational intelligence. The themes and structure of this special issue on cognitive informatics are described, and then, focuses of the selected papers in this special issue are highlighted.

Keywords: Cognitive informatics, natural intelligence, cognitive computing, abstract intelligence, artificial intelligence, neural informatics, denotational mathematics, computational intelligence

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1. Cognitive Informatics and Cognitive Computing

The theories of informatics and their perceptions on information as an abstract object have evolved from the classic information theory, modern informatics, to cognitive informatics in the past half century. *Classic informatics* [1, 5], particularly Shannon's information theory [5] known as the first-generation informatics, studies signals and channel behaviors based on statistics and probability theories. *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 both the original sources and final destinations of information. Therefore, any information must be cognized by human beings before it is understood and utilized in the society. This observation leads to the establishment of the third-generation informatics, a term coined by Wang in 2002 as *Cognitive Informatics* in [6, 8, 9, 10, 12, 13, 20].

Definition 1. *Cognitive informatics* (CI) is the transdisciplinary enquiry of cognitive and information sciences that investigates into the internal information processing mechanisms and processes of the brain and natural intelligence, and their engineering applications via an interdisciplinary approach.

A series of IEEE International Conferences on Cognitive Informatics (ICCI) have been annually organized. The inaugural ICCI event in 2002 was held in Calgary, Canada (ICCI'02) [21], followed by the events in London, UK (ICCI'03) [4], Victoria, Canada (ICCI'04) [2], Irvine, USA (ICCI'05) [3], Beijing, China (ICCI'06) [24], Lake Tahoe, USA (ICCI'07) [25], and Stanford University, USA (ICCI'08) [22].

The development and the cross fertilization between the aforementioned science and engineering disciplines have led to a whole range of extremely interesting new research topics in CI. The special issue on *Cognitive Informatics* in *Fundamenta Informaticae* (FI) covers selected papers on topics that transcend disciplinary boundaries of computing, cognitive science, and mathematics, which investigate the cognitive mechanisms and processes of human information processing, and their applications in computing and software engineering. This special issue has its focuses on the latest development in cognitive computing, neural informatics, abstract intelligence, denotational mathematics, and computational intelligence. The main themes of cognitive informatics encompass three categories of topics, i.e., cognitive computing, computational intelligence, and neural informatics, as shown in Table 1.

Across the three themes of cognitive informatics, their denotational and expressive needs lead to new forms of mathematics collectively known as denotational mathematics [11, 14, 19].

Definition 2. *Denotational mathematics* is a category of expressive mathematical structures that deals with high-level mathematical entities beyond numbers and sets, such as abstract objects, complex relations, behavioral information, concepts, knowledge, processes, and systems.

Typical forms of denotational mathematics are such as *concept algebra* [15], *system algebra* [16, 23], *Real-Time Process Algebra* (RTPA) [7, 11, 17, 19], and *Visual Semantic Algebra* (VSA) [18]. The paradigms of denotational mathematics provide a rigorous methodology and means for dealing with complex abstract entities in an extremely wide range of application areas such as cognitive computing, abstract intelligence, computational intelligence, software science, software engineering, and knowledge engineering.

The key application areas of CI can be divided into two categories. The first category of applications uses informatics and computing techniques to investigate cognitive science problems, such as memory,

Table 1. The Theoretical Framework of Cognitive Informatics

Cognitive Computing	**Computational Intelligence**	**Neural Informatics**
• Informatics models of the brain	• Imperative vs. autonomous Computing	• Neuroscience foundations of information processing
• Cognitive processes of the brain	• Reasoning and inferences	• Cognitive models of the brain
• Internal information processing Mechanisms	• Cognitive informatics foundations	• Functional modes of the brain
• Theories of natural intelligence	• Robotics	• Neural models of memory
• Intelligent foundations of computing	• Informatics foundations of software engineering	• Neural networks
• Denotational mathematics	• Fuzzy/rough sets/logic	• Neural computation
• Abstraction and means	• Knowledge engineering	• Cognitive linguistics
• Ergonomics	• Pattern and signal recognitions	• Neuropsychology
• Informatics laws of software	• Autonomic agent technologies	• Bioinformatics
• Knowledge representation	• Memory models	• Biosignal processing
• Models of knowledge and skills	• Software agent systems	• Cognitive signal processing
• Formal linguistics	• Decision theories	• Gene analysis and expression
• Cognitive complexity & metrics	• Problem solving theories	• Cognitive metrics
• Distributed intelligence	• Machine learning systems	• Neural signal interpretation
• Semantic computing	• Distributed objects/granules	• Visual information representation
• Emotions/motivations/attitudes	• Web contents cognition	• Visual semantics
• Perception and consciousness	• Nature of software	• Sensational cognitive processes
• Hybrid (AI/NI) intelligence	• Granular computing	• Human factors in systems

learning, and reasoning. The second category including the areas that use cognitive 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, retrieve, generation, 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 within the framework of CI.

2. Highlights of This Special Issue

This special issue on *Cognitive Informatics* in EATCS' *Fundamenta Informaticae* presents the latest advances in cognitive informatics and cognitive computing. The volume includes selected and refined papers from the 7th IEEE International Conference on Cognitive Informatics (ICCI 2008) at Stanford University, USA, held in August 2008 [22] and the 6th IEEE International Conference on Cognitive Informatics (ICCI 2007) at Lake Tahoe, USA, in August 2007 [25], as well as additional new contributions. This special issue is published in two parts. The first part of this special issue encompasses seven papers as highlighted below.

An intensive survey paper on "**A Doctrine of Cognitive Informatics (CI)**" is presented by a group of preeminent scientists in cognitive informatics encompassing *Yingxu Wang*, *Witold Kinsner*, *James A. Anderson*, *Du Zhang*, *Yiyu Yao*, *Philip Sheu*, *Jeffrey Tsai*, *Witold Pedrycz*, *Jean-Claude Latombe*, *Lotfi A. Zadeh*, *Dilip Patel*, and *Christine Chan*. Cognitive informatics (CI) develops a coherent set of fundamental theories and denotational mathematics, which form the foundation for most information and knowledge based science and engineering disciplines such as computer science, cognitive science, neuropsychology, systems science, cybernetics, software engineering, knowledge engineering, and computational intelligence. This paper reviews the central doctrine of CI and its applications. The theoretical framework of CI is described on the architecture of CI and its denotational mathematic means. A set of theories and formal models of CI is presented in order to explore the natural and computational intelligence. A wide range of applications of CI are described in the areas of cognitive computers, cognitive properties of knowledge, simulations of human cognitive behaviors, cognitive complexity of software, autonomous agent systems, and computational intelligence.

Louis ten Bosch, Hugo Van Hamme, Lou Boves, and *Roger K. Moore* present "**A Computational Model of Language Acquisition: The Emergence of Words.**" In this paper, a computational model is proposed that is able to detect and build word-like representations on the basis of sensory input. The model is designed and tested with a further aim to investigate how infants may learn to communicate by means of spoken languages. The computational model adopts a memory, a perception module, and the concept of 'learning drive'. Learning takes place within a communicative loop between a 'caregiver' and the 'learner'. Experiments carried out on three European languages with different genetic backgrounds (Finnish, Swedish, and Dutch) show that a robust word representation can be learned in using less than 100 acoustic tokens of that word. The model is inspired by the memory structure that is assumed functional for human cognitive processing.

Shusaku Tsumoto and *Shoji Hirano* present "**Statistical Independence and Determinants in a Contingency Table – Interpretation of Pearson Residuals Based on Linear Algebra.**" This paper analyzes Pearson residuals, which is an important element of chi-square test statistic, in a contingency table from the viewpoint of matrix theory. First, a given contingency table is viewed as a matrix and the residual of each element in a matrix is obtained as the difference between observed values and expected values calculated by marginal distributions. Then, each residual is decomposed into the linear sum of the 2×2 subderminants of an original matrix, except for the i-th column and j-th row. Furthermore, the number of the determinants is equal to the degree of freedom for the chi-square test statistic for a given contingency table. Thus, 2×2 subdeterminants in a contingency matrix determine the degree of statistical independence of two attributes as elementary granules.

Jun Peng, Du Zhang, and *Xiaofeng Liao* present "**A Digital Image Encryption Algorithm Based on Hyper-Chaotic Cellular Neural Network.**" Using Chaotic characteristics of dynamic system is a promising direction to design cryptosystems that play a pivotal role in a very important engineering application of cognitive informatics. However, encryption algorithms based on the low dimensional chaotic maps face a potential risk of the key stream being reconstructed via return map technique or neural network method. In this paper, the authors propose a new digital image encryption algorithm that employs a hyper-chaotic cellular neural network. To substantiate its security characteristics, the authors conduct the following security analyses of the proposed algorithm: key space analysis, sensitivity analysis, information entropy analysis, and correlation coefficients analysis of adjacent pixels. The results demonstrate that the proposed encryption algorithm has desirable security properties and can be deployed as a cornerstone in a sound security cryptosystem. The proposed algorithm is compared with five other chaos-based image encryption algorithms, and a better security performance of the hyper-Chaotic Encryption algorithm has been obtained.

Yingxu Wang presents "**Paradigms of Denotational Mathematics for Cognitive Informatics and Cognitive Computing.**" Denotational mathematics is a category of expressive mathematical structures that deals with high-level mathematical entities beyond numbers and sets, such as abstract objects, complex relations, behavioral information, concepts, knowledge, processes, and systems. Denotational mathematics is usually in the form of abstract algebra that is a branch of mathematics in which a system of abstract notations is adopted to denote relations of abstract mathematical entities and their algebraic operations based on given axioms and laws. Four paradigms of denotational mathematics, known as concept algebra, system algebra, Real-Time Process Algebra (RTPA), and Visual Semantic Algebra (VSA), are introduced in this paper. Applications of denotational mathematics in cognitive informatics and computational intelligence are elaborated. Denotational mathematics is widely applicable to model and manipulate complex architectures and behaviors of both humans and intelligent systems, as well as long chains of inference processes.

Luis Llana and *Manuel Núñez* present "**Testing Semantics for RTPA.**" A denotational mathematics known as Real-Time Process Algebra (RTPA) has been created by Wang in 2002 that enables rigorous treatment of knowledge representation and manipulation in terms of *to be* / *to have* / *to do* categories in a formal and coherent framework. RTPA has been designed to cope with the three dimensions involved in the problem of software specification: (i) mathematical operations, (ii) event/process timing, and (iii) memory manipulation. In this paper, a testing semantics to the second dimension - the process timing dimension - is proposed. An SOS-like operational semantics is described for the process relations of RTPA. Then, the concept of semantic test is introduced and applied to RTPA processes. Finally, an operational characterization that can be used as a first step to define a denotational semantics is proposed with respect to the testing semantics.

Ali Kamandi and *Jafar Habibi* present "**A Comparison of Metric-Based and Empirical Approaches for Cognitive Analysis of Modeling Languages.**" It is recognized that modeling languages are needed to describe the conceptual construct underlying software. Cognitive complexity is one of the common problems in designing modeling languages. Users have to split their attention and cognitive resources between two different tasks when working with complex language: solving the problem and understanding the elements composing the language. Several studies have been accomplished to evaluate cognitive complexity of modeling languages. Among them, metric based and empirical approaches are more important and convenient than others. The metric-based and empirical approaches of cognitive analyses are compared in this paper. Results show that there is no significant relation between outputs generated by the two different approaches.

The editors expect that the readers of the journal of *Fundamenta Informaticae* will benefit from the papers presented in this special issue on the latest advances in theories and applications of cognitive informatics, natural intelligence, abstract intelligence, denotational mathematics, cognitive computing, and computational intelligence.

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References

[1] Bell, D.A. (1953), *Information Theory*, Pitman, London.

[2] Chan, C., W. Kinsner, Y. Wang, and D.M. Miller eds. (2004), *Proc. 3rd IEEE International Conference on Cognitive Informatics (ICCI'04)*, IEEE CS Press, Victoria, Canada, Aug.

[3] Kinsner, W., D. Zhang, Y. Wang, and J. Tsai eds. (2005), *Proc. 4th IEEE International Conference on Cognitive Informatics (ICCI'05)*, IEEE CS Press, Irvine, California, USA, Aug.

[4] Patel, D., S. Patel, and Y. Wang eds. (2003), *Cognitive Informatics: Proc. 2nd IEEE International Conference (ICCI'03)*, IEEE CS Press, London, UK, Aug.

[5] Shannon, C.E. (1948), A Mathematical Theory of Communication, *Bell System Technical Journal*, 27, 379-423 and 623-656.

[6] Wang, Y. (2002a), Keynote: On Cognitive Informatics, Keynote, *Proc. 1st IEEE International Conference on Cognitive Informatics (ICCI'02)*, Calgary, Canada, IEEE CS Press, August, 34-42.

[7] Wang, Y. (2002b), The Real-Time Process Algebra (RTPA), *Annals of Software Engineering*, Springer, USA, 14, 235-274.

[8] Wang, Y. (2003), On Cognitive Informatics, *Brain and Mind: A Transdisciplinary Journal of Neuroscience and Neurophilosophy*, 4(2), 151-167.

[9] Wang, Y. (2006a), Keynote: Cognitive Informatics - Towards the Future Generation Computers that Think and Feel, *Proc. 5th IEEE International Conference on Cognitive Informatics (ICCI'06)*, Beijing, China, IEEE CS Press, July, 3-7.

[10] Wang, Y. (2006b), On the Informatics Laws and Deductive Semantics of Software, *IEEE Transactions on Systems, Man, and Cybernetics (Part C)*, 36(2), 161-171.

[11] Wang, Y. (2007a), *Software Engineering Foundations: A Software Science Perspective*, CRC Series in Software Engineering, Vol. II, CRC Press, USA, July.

[12] Wang, Y. (2007b), The Theoretical Framework of Cognitive Informatics, *International Journal of Cognitive Informatics and Natural Intelligence*, IGI Publishing, USA, 1(1), 1-27.

[13] Wang, Y. (2007c), Keynote: Cognitive Informatics Foundations of Nature and Machine Intelligence, *Proc. 6th IEEE International Conference on Cognitive Informatics (ICCI'07)*, IEEE CS Press, Lake Tahoe, CA, USA, July, August, 3-12.

[14] Wang, Y. (2008a), On Contemporary Denotational Mathematics for Computational Intelligence, *Transactions on Computational Science*, Springer, Aug., 2, 6-29.

[15] Wang, Y. (2008b), On Concept Algebra: A Denotational Mathematical Structure for Knowledge and Software Modeling, *International Journal of Cognitive Informatics and Natural Intelligence*, IGI Publishing, USA, 2(2), 1-19.

[16] Wang, Y. (2008c), On System Algebra: A Denotational Mathematical Structure for Abstract System modeling, *International Journal of Cognitive Informatics and Natural Intelligence*, IGI Publishing, USA, 2(2), 20-42.

[17] Wang, Y. (2008d), RTPA: A Denotational Mathematics for Manipulating Intelligent and Computational Behaviors, *International Journal of Cognitive Informatics and Natural Intelligence*, IGI Publishing, USA, 2(2), 44-62.

[18] Wang, Y. (2008e), On Visual Semantic Algebra (VSA) and the Cognitive Process of Pattern Recognition, *Proc. 7th International Conference on Cognitive Informatics (ICCI'08)*, IEEE CS Press, Stanford University, CA., Aug., 384-393.

[19] Wang, Y. (2008f), Mathematical Laws of Software, *Transactions of Computational Science*, Springer, Aug., 2, 46-83.

[20] Wang, Y. (2009), On Abstract Intelligence: Toward a Unified Theory of Natural, Artificial, Machinable, and Computational Intelligence, *International Journal of Software Science and Computational Intelligence*, IGI, USA, 1(1), 1-17.

[21] Wang, Y., R. Johnston, and M. Smith eds. (2002), Cognitive Informatics: *Proc. 1st IEEE International Conference (ICCI'02*), IEEE CS Press, Calgary, AB, Canada, August.

[22] Wang, Y., D. Zhang, J.C. Latombe, and W. Kinsner eds. (2008), *Proc. 7th IEEE International Conference on Cognitive Informatics (ICCI'08)*, IEEE CS Press, Stanford University, CA, USA, July.

[23] Wang, Y., L.A. Zadeh, and Y. Yao (2009), On the System Algebra Foundations for Granular Computing, *International Journal of Software Science and Computational Intelligence*, IGI, USA, Jan., 1(1), 64-86.

[24] Yao, Y., Z. Shi., Y. Wang, and W. Kinsner eds. (2006), *Proc. 5th IEEE International Conference on Cognitive Informatics (ICCI'06)*, IEEE CS Press, Beijing, China, July.

[25] Zhang, D., Y. Wang, and W. Kinsner eds. (2007), *Proc. 6th IEEE International Conference on Cognitive Informatics (ICCI'07)*, IEEE CS Press, Lake Tahoe, CA, USA, July.