

On Cognitive Computing

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ABSTRACT

Inspired by the latest development in cognitive informatics and contemporary denotational mathematics, cognitive computing is an emerging paradigm of intelligent computing methodologies and systems, which implements computational intelligence by autonomous inferences and perceptions mimicking the mechanisms of the brain. This article presents a survey on the theoretical framework and architectural techniques of cognitive computing beyond conventional imperative and autonomic computing technologies. Theoretical foundations of cognitive computing are elaborated from the aspects of cognitive informatics, neural informatics, and denotational mathematics. Conceptual models of cognitive computing are explored on the basis of the latest advances in abstract intelligence and computational intelligence. Applications of cognitive computing are described from the aspects of autonomous agent systems and cognitive search engines, which demonstrate how machine and computational intelligence may be generated and implemented by cognitive computing theories and technologies toward autonomous knowledge processing. [Article copies are available for purchase from InfoSci-on-Demand.com]

Keywords: Autonomous Agent Systems; Autonomous Systems; Cognitive Computing; Cognitive Informatics; Cognitive Search Engines; Computational Intelligence; Denotational Mathematics; Natural Intelligence; Neural Informatics; Soft Computing

INTRODUCTION

Computing as a discipline in a narrow sense, is an application of computers to solve a given computational 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 behaviors.

According to theories of cognitive informatics (Wang, 2002a, 2003, 2006, 2007b, 2007c, 2008a, 2009a; Wang et al., 2009b), computing technologies and systems may be classified into the categories of imperative, autonomic, and cognitive from the bottom up. Imperative computing is a traditional and

passive technology based on stored-program controlled behaviors for data processing (Turing, 1950; von Neumann, 1946, 1958; Gersting, 1982; Mandrioli and Ghezzi, 1987; Lewis and Papadimitriou, 1998). An autonomic computing is goal-driven and self-decision-driven technologies that do not rely on instructive and procedural information (Kephart and Chess, 2003; IBM, 2006; Wang, 2004, 2007a). Cognitive computing is more intelligent technologies beyond imperative and autonomic computing, which embodies major natural intelligence behaviors of the brain such as thinking, inference, learning, and perceptions.

Definition 1. *Cognitive computing is an emerging paradigm of intelligent computing methodologies and systems that implements computational intelligence by autonomous inferences and perceptions mimicking the mechanisms of the brain.*

Cognitive computing systems are designed for cognitive and perceptive knowledge processing based on contemporary denotational mathematics (Zadeh, 1965; Wang, 2002b, 2007a, 2008b, 2008c, 2008d, 2008e; Wang et al., 2009a), which are centered by the parallel autonomous inference and perception mechanisms of the brain as revealed in the Layered Reference Model of the Brain (LRMB) (Wang et al., 2006). On the basis of cognitive computing, next generation cognitive computers and autonomous intelligent systems that think and feel may be designed and implemented.

This article presents the theoretical framework and architectural techniques of cognitive computing beyond conventional imperative and autonomic computing systems. Theoretical foundations of cognitive computing are elaborated from the aspects of cognitive informatics, neural informatics, and denotational mathematics. Conceptual models of cognitive computing are explored from the latest development in abstract intelligence, intelligent behaviors, and computational intelligence. Applications of cognitive computing are described with an autonomous agent system and a cognitive search engine, which demonstrate how machine and computational intelligence may be generated and implemented by cognitive computing theories and technologies toward autonomous knowledge processing.

THEORETICAL FOUNDATIONS FOR COGNITIVE COMPUTING

Theories and methodologies of cognitive computing are inspired by the latest advances in cognitive informatics and denotational mathematics. This section elaborates the cognitive

informatics theories and denotational mathematical structures for cognitive computing.

Cognitive Informatics for Cognitive Computing

The fundamental theories and methodologies underpinning cognitive computing are cognitive informatics (Wang, 2002a, 2003, 2006, 2007b, 2007c, 2008a, 2009a; Wang et al., 2009b). Cognitive informatics is a cutting-edge and multidisciplinary research field that tackles the fundamental problems shared by modern informatics, computation, software engineering, AI, computational intelligence, cybernetics, cognitive science, neuropsychology, medical science, systems science, philosophy, linguistics, economics, management science, and life sciences. The development and the cross fertilization between the aforementioned science and engineering disciplines have led to a whole range of emerging research areas known as cognitive informatics.

Definition 2. *Cognitive informatics is a trans-disciplinary enquiry of cognitive, computing, and information sciences, which studies the internal information processing mechanisms and processes of natural intelligence (the brain), the theoretical framework and denotational mathematics of abstract intelligence, and their engineering applications by cognitive computing.*

The architecture of the theoretical framework of cognitive informatics (Wang, 2007b) covers the Information-Matter-Energy (IME) model (Wang, 2003), the Layered Reference Model of the Brain (LRMB) (Wang et al., 2006), the Object-Attribute-Relation (OAR) model of information representation in the brain (Wang, 2007d), the cognitive informatics model of the brain (Wang and Wang, 2006), Natural Intelligence (NI) (Wang, 2002a), Neural Informatics (NeI) (Wang, 2007b), the mechanisms of human perception processes (Wang, 2007e), and cognitive computing (Wang, 2006).

Recent studies in cognitive informatics reveal an entire set of cognitive functions of the brain (Wang, 2007b; Wang and Wang, 2006) and their cognitive process models (Wang et al., 2006) known as the LRMB model of the brain. LRMB, as shown in Figure 1, provides a reference model for the design and implementation of computational intelligence, which enables a systematic and formal description of architectures and behaviors of computational intelligence. The LRMB model explains 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 from the bottom up. LRMB elicits the core and highly repetitive recurrent cognitive processes from a huge variety of life functions, which may shed light on the study of the fundamental mechanisms and interactions of complicated mental processes and computational intelligence, particularly the relationships and interactions between the inherited and the acquired life functions as well as those of the subconscious and conscious cognitive processes.

The seven-layer LRMB model can be refined by 43 cognitive processes as shown in

Figure 2. Based LRMB, any specific life behavior in real-world is a revoke or composition of these LRMB cognitive processes interacting at different layers.

Cognitive informatics prepares a systematic theoretical foundation for the development of cognitive computing methodologies and systems. The architectural and behavioral models of cognitive computing will be developed in the next section on the basis of the theoretical framework of cognitive informatics.

Neural Informatics for Cognitive Computing

Neural informatics (Wang, 2007b) is a branch of cognitive informatics, where memory and its neural and logical models are recognized as the foundation and platform of any form of natural or artificial intelligence (Wang and Wang, 2006).

Definition 3. *Neural Informatics is an interdisciplinary enquiry of the biological and physiological representation of information and knowledge in the brain at the neuron level and their abstract modeling in denotational mathematics.*

Figure 1. The Layered Reference Model of the Brain (LRMB)

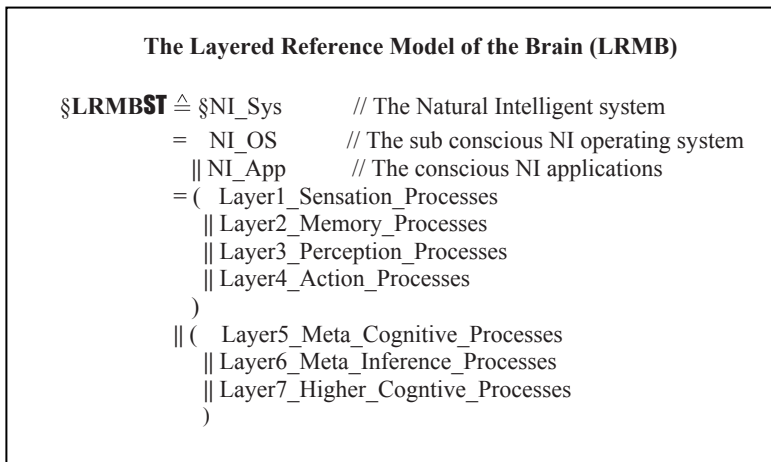
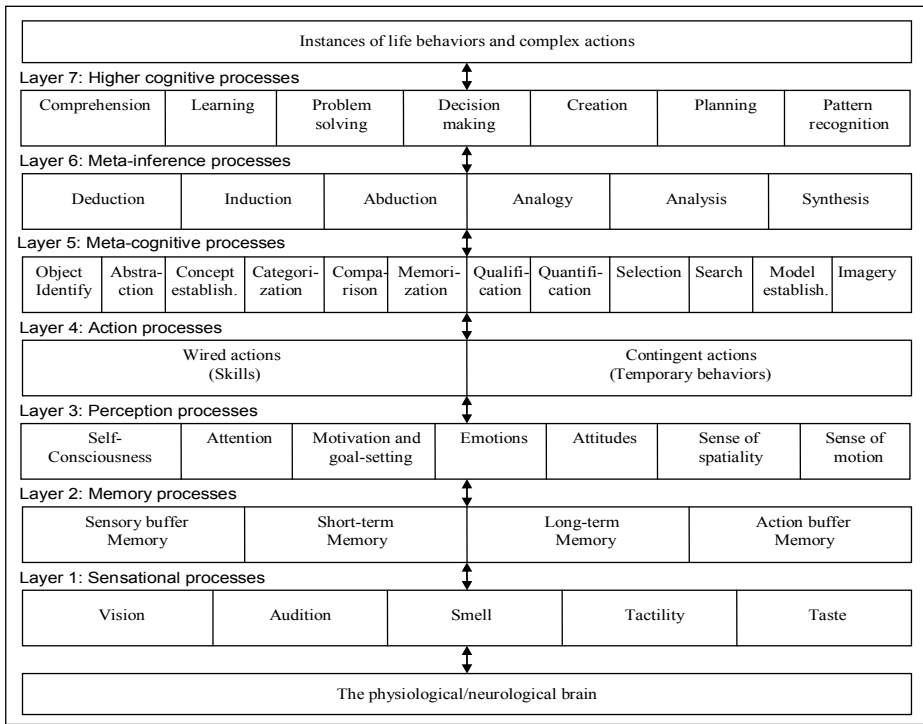


Figure 2. The refined model of LRMB



The major memory organ that accommodates acquired information and knowledge in the brain is the cerebrum or the cerebral cortex. In particular, the association and premotor cortex in the frontal lobe, the temporal lobe, sensory cortex in the frontal lobe, visual cortex in the occipital lobe, primary motor cortex in the frontal lobe, supplementary motor area in the frontal lobe, and procedural memory in cerebellum (Wilson and Frank, 1999; Wang and Wang, 2006).

Theorem 1. *The Cognitive Model of Memory (CMM) states that the logical architecture of human memory is parallel configured by the Sensory Buffer Memory (SBM), Short-Term Memory (STM), Conscious-Status Memory (CSM), Long-Term Memory (LTM), and Action-Buffer Memory (ABM), i.e.:*

$$\text{CMMST} \triangleq \begin{array}{|l} \text{SBM} \\ \text{STM} \\ \text{CSM} \\ \text{LTM} \\ \text{ABM} \end{array} \tag{1}$$

where $||$ denotes a parallel relations and ST represents an abstract system structural model.

CMM provides a logical model for explaining the abstract functional partitions of memories and their roles. In Theorem 1, ABM and CSM are newly identified in (Wang and Wang, 2006), which were not modeled in literature of cognitive science, psychology, neurology, and brain science. The CMM model may be used to explain a set of fundamental mechanisms of neural informatics.

It is recognized that in contrary to the traditional *container* metaphor, the mechanisms of

human memory can be described by a *relational* metaphor. The relational metaphor perceives that memory and knowledge are represented by the connections between neurons known as the synapses, rather than the neurons themselves as information containers. Therefore, the cognitive model of human memory, particularly LTM, can be described by three fundamental artefacts known as: a) *Objects* – an abstraction of an external entity and/or internal concept; b) *Attribute* – a sub-object that is used to denote detailed properties and characteristics of the given object; and c) *Relation* – a connection or inter-relationship between any pair of object-object, object-attribute, and attribute-attribute.

Definition 4. *The Object-Attribute-Relation (OAR) model of LTM is described as a triple, i.e.:*

$$OAR \triangleq (O, A, R) \tag{2}$$

An illustration of the OAR model between two objects is shown in Figure 3. The relations between objects O_1 and O_2 can be established via pairs of object-object, object-attribute, and/or attribute-attribute. The connections could be highly complicated, while the mechanism is fairly simple that it can be reduced to the physiological links of neurons via synapses in LTM.

It is noteworthy as in the OAR model that the *relations* themselves represent information and knowledge in the brain. The relational metaphor is totally different from the traditional container metaphor in neuropsychology and computer science, because the latter perceives that memory and knowledge are *stored* in individual neurons and the neurons function as containers.

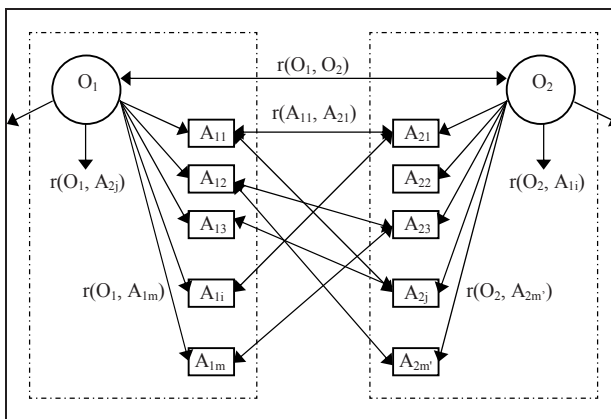
Denotational Mathematics for Cognitive Computing

As that of formal logic and Boolean algebra are the mathematical foundations of von Neumann computers. The mathematical foundations of cognitive computing are based on contemporary denotational mathematics (Wang, 2008b).

Definition 5. *Denotational mathematics is a category of expressive mathematical structures that deals with high-level mathematical entities beyond numbers and simple sets, such as abstract objects, complex relations, behavioral information, concepts, knowledge, processes, intelligence, and systems.*

Typical paradigms of denotational mathematics are comparatively presented in Table 1, where their structures, mathematical entities, algebraic operations, and usages are contrasted.

Figure 3. The OAR model of memory mechanisms



The paradigms of denotational mathematics as shown in Table 1 are concept algebra (Wang, 2008c), system algebra (Wang, 2008d; Wang et al., 2009a), and Real-Time Process Algebra (RTPA) (Wang, 2002b, 2008e). Among the three forms of denotational mathematics, concept algebra is designed to deal with the abstract mathematical structure of concepts and semantic inferences, as well as their representation and manipulation in semantic computing and knowledge engineering. System algebra is created to the rigorous treatment of abstract systems and their algebraic relations and operations. RTPA is developed to deal with series of intelligent behavioral processes of humans and systems.

The emergence of denotational mathematics is driven by the practical needs in cognitive informatics, computational intelligence, computing science, software science, and knowledge engineering, because all these modern disciplines study complex human and machine behaviors and their rigorous treatments. Denotational mathematics provides a powerful mathematical means for modeling and formalizing cognitive computing systems. Not only the architectures of computational intelligent systems, but also their dynamic behaviors can be rigorously and systematically manipulated by denotational mathematics. A wide range of problems and applications have been dealt with by denotational mathematics in cognitive informatics and computational intelligence, such as autonomous machine learning (Wang, 2007f), memorization (Wang, 2009b), cognitive decision making (Wang and Ruhe, 2007), and problem solving (Wang and Chiew, 2009). The case studies in cognitive computing demonstrate that denotational mathematics is an ideal and powerful mathematical means for dealing with concepts, knowledge, behavioral processes, and human/machine intelligence with real-world problems.

MODELS OF COGNITIVE COMPUTING

On the basis of cognitive informatics and denotational mathematics, new computing architectures and technologies may be developed known as cognitive computing, which adopt non-von Neumann architectures and extend traditional computing capabilities from imperative data processing to autonomous knowledge processing. The following subsections describe the abstract intelligence and behavioral models of cognitive computing.

The Abstract Intelligence Model of Cognitive Computing

According to functional reductionism, a logical model of the general form of intelligence is needed known as abstract intelligence in order to formally explain high-level mechanisms of the brain on the basis of observations at the biological, physiological, functional, and logical levels. On the basis of the logical model of abstract intelligence, the studies on the paradigms of intelligence, such as natural, artificial, machinable, and computational intelligence, may be unified into a coherent framework (Wang, 2009a).

Definition 6. *Abstract intelligence, αI , is a human enquiry of both natural and artificial intelligence at the embody levels of neural, cognitive, functional, and logical from the bottom up.*

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 autonomous systems. 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 2.

Table 2. 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 abstract intelligence share the same cognitive informatics foundation as described in the following theorem, because they are an artificial or machine implementation of abstract intelligence. Therefore, the differences between NI, AI, MI, and CoI are only distinguishable by the means of their implementation and the extent of their intelligent capability.

Theorem 2. *The inclusive intelligent capability states that any concrete real-world paradigm of intelligence is a subset of αI , i.e.:*

$$CoI \subseteq MI \subseteq AI \subseteq NI \subseteq \alpha I \quad (3)$$

Theorem 2 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, according to Theorem 2, the development and implementation of AI rely on the understanding of the mechanisms and laws of NI.

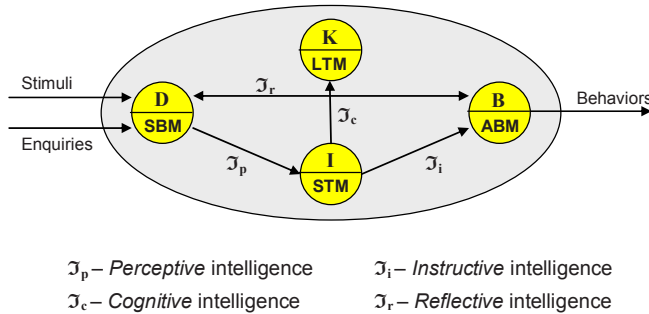
As an embedment form of abstract intelligence, cognitive computing is a subset of αI and NI. Therefore, cognitive computing shares the LRMB reference model of the brain, which extends capabilities of CoI to the seven layers of NI. Detailed discussions will be extended in the following subsections.

The Computational Intelligence Model of Cognitive Computing

Definition 7. *Computational intelligence (CoI) is an embodying form of abstract intelligence (αI) that implements intelligent mechanisms and behaviors by computational methodologies and software systems, such as expert systems, fuzzy systems, autonomous computing, intelligent agent systems, genetic/evolutionary systems, and autonomous learning systems.*

The fundamental mechanisms of αI can be described by the Generic Abstract Intelligence Model (GAIM) (Wang, 2007c) as shown in Figure 4. In the GAIM model, different forms of intelligence are described as a driving force that transfers between a pair of abstract objects in the brain such as data (D), information (I), knowledge (K), and behavior (B). It is noteworthy that each abstract object is physically

Figure 4. The Generic Abstract Intelligence Model (GAIM)



retained in a particular type of memories. This is the neural informatics foundation of natural intelligence, and the physiological evidences of why natural intelligence can be classified into four forms known as the instructive intelligence I_i , reflective intelligence I_r , cognitive intelligence I_c , and perceptive intelligence I_p .

Cognitive computing is aimed at implementing all forms of abstract intelligence in the GAIM model by imperative computing C_p , autonomic computing C_A , and cognitive computing C_C from the bottom up. The relationship between different forms of CoI and their implementation means can be elaborated as follows:

$$\begin{cases} C_I \Rightarrow \mathcal{J}_i \\ C_A \Rightarrow \mathcal{J}_r \\ C_C \Rightarrow \mathcal{J}_c \cup \mathcal{J}_p \end{cases} \quad (4)$$

where each form of cognitive computing will be specified by a set of intelligent computational behaviors in the following subsection.

The Behavioral Model of Cognitive Computing

The abstract intelligence model of cognitive computing can be refined by a behavioral model that evolves computing technologies from the conventional imperative behaviors to the autonomic and cognitive behaviors.

Definition 8. The entire behavior space of cognitive computing, B_{CC} is a layered hierarchical structure that encompasses the imperative behaviors B_p , autonomic behaviors B_A , and cognitive behaviors B_C from the bottom up, i.e. (see Box 1) where B_I is modeled by the event-, time-, and interrupt-driven behaviors; B_A is modeled by the goal- and decision-driven behaviors; and B_C is modeled by the perception- and inference-driven behaviors.

On the basis of the above model, the intelligent behaviors of I_i , I_A , and I_C can be defined as follows.

Definition 9. The behavioral model of cognitive computing, C_C **ST**, is to implement the imperative intelligence I_p , autonomic intelligence I_A , and cognitive intelligence I_C as follows (see Box 2).

According to Definition 9, it is obvious that the relationship among the three-level intelligence can be derived as follows.

Theorem 3. The intelligent behaviors of cognitive computing systems are hierarchical and inclusive at the levels of imperative, autonomic, and cognitive intelligence, i.e.:

$$\mathcal{J}_I \subseteq \mathcal{J}_A \subseteq \mathcal{J}_C \quad (7)$$

Box 1.

$$\begin{aligned}
 B_{CC} &\triangleq (B_I, B_A, B_C) \\
 &= \left(\begin{array}{ll} \{B_e, B_t, B_{int}\} & // B_I \\ || \{B_e, B_t, B_{int}, B_g, B_d\} & // B_A \\ || \{B_e, B_t, B_{int}, B_g, B_d, B_p, B_{inf}\} & // B_C \end{array} \right) \quad (5)
 \end{aligned}$$

Box 2.

$$C_C \mathbf{ST} \triangleq \begin{cases} \mathcal{J}_I = \{B_e, B_t, B_{int}\} \\ \mathcal{J}_A = \{B_e, B_t, B_{int}, B_g, B_d\} \\ \mathcal{J}_C = \{B_e, B_t, B_{int}, B_g, B_d, B_p, B_{inf}\} \end{cases} \quad (6)$$

Proof: *Directly applying Definition 9, Theorem 3 can be proven, which shows that any lower level intelligent behavior is a subset of those of a higher level. In other words, any higher layer intelligence is a natural extension of those of lower layers.*

Both Theorem 3 and Definition 9 indicate the approach to implement cognitive computing at the top level of computational intelligence is to embody and implement a set of parallel computing architectures and behaviors by imperative, autonomic, and cognitive engines.

APPLICATIONS OF COGNITIVE COMPUTING

Cognitive computing as generic intelligence/knowledge processing methodology and technology can be applied to develop the next generation cognitive computers and autonomous systems. Two paradigms of cognitive computing known as autonomous agent systems and cognitive search engines are elaborated in this section, which mimic higher level intelligent

capabilities of αI and NI beyond conventional imperative computing.

Autonomous Agent Systems

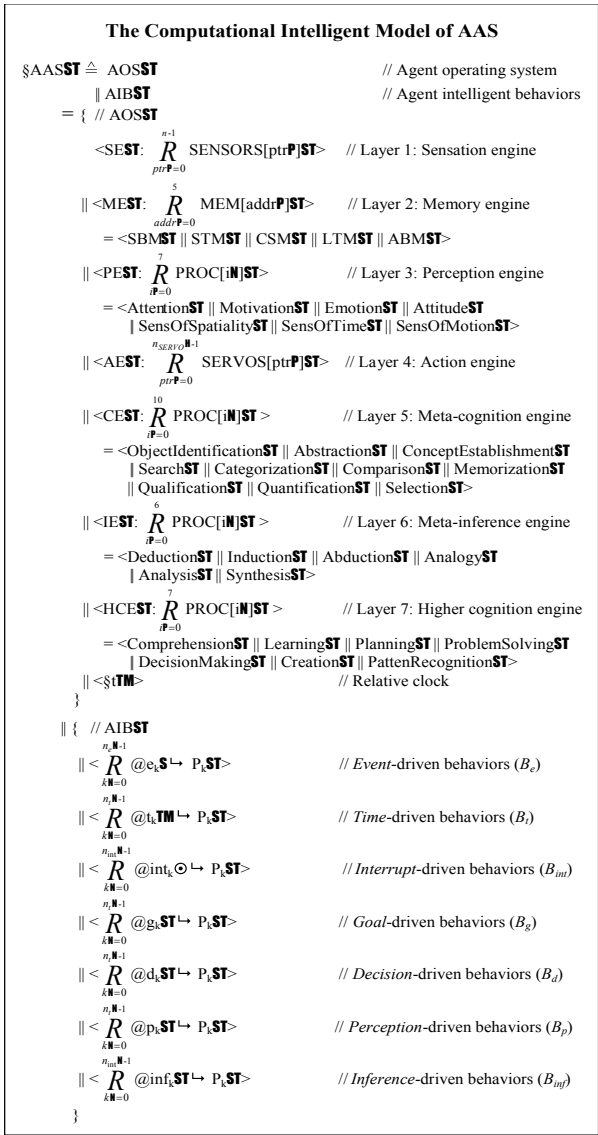
Definition 10. *An Autonomous Agent System (AAS) is a composition of distributed agents that possesses autonomous computing and decision making abilities as well as interactive communication capability to peers and the environment.*

An AAS may also be called an intelligentware, shortly intelware (Wang, 2009c), to reflect its essence and relationship with hardware and software in cognitive computing. On the basis of LRMB, an AAS can be modeled as follows.

Definition 11. *The cognitive computing model of AAS's, $\S AAS\mathbf{ST}$, is a parallel structure represented by the Agent Operating System (AOS \mathbf{ST}) and a set of agent intelligence represented by the Agent Intelligent Behaviors (AIB \mathbf{ST}), as shown in Figure 5.*

The $\S AAS\mathbf{ST}$ model, denoted in RTPA (Wang, 2002b, 2008e), reveals that NI and AI share the same cognitive informatics founda-

Figure 5. The cognitive computing model of AAS



tions on the basis of abstract intelligence and cognitive computing. The compatible intelligent capability states that NI, AI, and AAS's, are compatible by sharing the same mechanisms of intelligent capability and behaviors. In other words, at the logical level, NI of the brain shares the same mechanisms as those of AI and computational intelligence. The differences

between NI and AI are only distinguishable by the means of implementation and the extent of intelligent ability. Therefore, the studies on NI and AI in general, and AAS's in particular, may be unified into a coherent framework based on cognitive informatics and cognitive computing, especially the LRMB reference model.

Cognitive Search Engines

Search is not only a basic computational application, but also a fundamental cognitive process of human brains. The study in cognitive search engines is another application paradigm of cognitive computing.

Definition 12. Search \mathcal{SE} is a cognitive process to allocate and retrieve a piece of knowledge in the memory and/or cyberspace by a given concept $c\mathbf{ST}$, in which an equivalent or similar concept $c_i\mathbf{ST}$ may be found, i.e.:

$$\mathcal{SE} \bigcup_{i=1}^{n\mathbf{N}} c\mathbf{ST} \hat{=} c_i\mathbf{ST} \vee c\mathbf{ST} \cong c_i\mathbf{ST} \rightarrow c'\mathbf{ST} = c\mathbf{ST} \uplus c_i\mathbf{ST} \quad (8)$$

where $n\mathbf{N}$ is the maximum number of elements in the designated searching space in LTM or cyberspace, and $c\mathbf{ST} = c_i\mathbf{ST}$ or $c\mathbf{ST} \cong c_i\mathbf{ST}$ denote an equivalent or similar concept according to concept algebra.

A fundamental problem in search technologies is that search is a hybrid and complex process encompassing the following three aspects: a) Queries comprehension, b) Search algorithms, and c) Results representation. An

analysis and contrast of conventional search and intelligent search by cognitive computing systems on these three aspects are provided in Table 3.

It is recognized that suitable denotational mathematical means, such as concept algebra (Wang, 2008c) and visual semantic algebra (Wang, 2009d) are required in order to support rigorous textual and visual semantic reasoning with relational linguistic/domain knowledge bases. In addition, machine learning capabilities and sophisticated computational intelligence are needed. Therefore, cognitive computing provides a set of theoretical and technical preparations for the design and implementation of next generation intelligent search engines.

CONCLUSION

Cognitive computing has been characterized as a set of autonomous and perceptive knowledge processing theories and technologies mimicking the mechanisms of the brain beyond conventional imperative data processing. This article has presented the theoretical framework of cognitive computing and recent advances in the study of cognitive computing theories and methodologies in cognitive informatics, soft

Table 3. Comparison of search technologies

Function	Conventional Search Engines	Cognitive Search Engines
Query	Keyword-based (syntactic-oriented)	Comprehension-based (semantics-oriented)
	Symbolic guessing of user queries	Interactive semantic analysis of user queries
Search	Keyword matching (symbolic equivalence)	Semantic matching (conceptual/semantic equivalence)
	Finding all equivalent symbol strings	Finding all synonymies and related knowledge
Results representation	A list of URLs	A list of concepts with attributes and objects
	Ranking by: - Keyword frequency - Statistical or probable benchmarks	Ranking by: - Concept equivalency - Semantic similarity
	Knowledge processing: - None	Knowledge processing: - Knowledge extraction - Concept building

computing, and computational intelligence. Conceptual and behavioral models of cognitive computing have been elaborated. A powerful mathematical means known as denotational mathematics have been introduced to deal with the design and implementation of cognitive computing systems. A wide range of applications of cognitive computing have been identified such as autonomous agent systems and intelligent search engines. The pilot projects have demonstrated how machine and computational intelligence may be generated and implemented by cognitive computing theories and technologies toward next generation computing systems that think and feel.

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