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On Cognitive Informatics

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Abstract. Supplementary to matter and energy, information is the third essence for modeling the natural world. An emerging discipline known as *cognitive informatics* (CI) is developed recently that forms a profound interdisciplinary study of cognitive and information sciences, and tackles the common root problems sharing by informatics, computing, software engineering, artificial intelligence, cognitive science, neuropsychology, philosophy, linguistics, and life science. CI focuses on internal information processing mechanisms and the natural intelligence of the brain. This paper describes the historical development of informatics from the classical information theory and contemporary informatics, to CI. The domain of CI, and its interdisciplinary nature are explored. Foundations of CI, particularly the brain versus the mind, the acquired life functions versus the inherited ones, and generic relationships between information, matter, and energy are investigated. The potential engineering applications of CI and perspectives on future research are discussed. It is expected that the investigation into CI will result in fundamental findings towards the development of next generation IT and software technologies, and new architectures of computing systems.

Key words: AI, cognitive informatics, cognitive science, computing, contemporary informatics, information theory, neuropsychology, philosophy, software engineering.

1. Introduction

Information is the third essence of the natural world supplementing matter and energy. Informatics, the science of information, studies the nature of information, its processing, and ways of transformation between information, matter, and energy. Informatics has been developed from the classical information theory (Hartley, 1928; Shannon, 1948; Shannon and Weaver, 1949; Bell, 1953; Goldman, 1953; Patel and Wang, 2000), contemporary informatics (Zhong, 1996; Wang, 2001, 2002), to cognitive informatics (CI) (Wang, 2001, 2002a,b; Wang *et al.*, 2001, 2002, 2003; Wang and Wang, 2002) in the past half century.

Cognitive informatics is a transdisciplinary expansion of information science that studies computing and information processing problems by using cognitive science and neuropsychology theories, and studies the cognitive information processing mechanisms of the brain by using computing and informatics theories.

It is interesting to note that philosophers all over the world shared similar perceptions towards cognition, information, and the natural intelligence. A famous historical story told that when two Chinese philosophers walking around a lake and seeing fishes swimming and jumping lively and freely in the water, the following dialogue was stimulated (Zhuang Tsui, 369 – 286 BC, Chuang Tsui • Outer Chapters, Chapter 17, Autumn Water):

Philosopher A: The fishes must be very happy because they are lively playing in the lake.

Philosopher B: Well, you are not a fish. How do you know that they are happy?

Philosopher A: Then, you are not me. How do you know that I don't know the feeling of the fishes.

Philosopher B: Just as I am not you, I don't know you; You are not a fish, therefore you don't know the feeling of the fishes.

Philosopher A: As you claiming that I don't know something, you implied you know what I know. Therefore, I am able to perceive what is the meaning of the fishes' behavior as well.

This is a good situation to demonstrate the objectives of the study in CI – how we, as human beings, acquire, process, interpret, and express information by using the brain, and how we understand the minds of different individuals.

Rene Descartes (1596–1650), French philosopher and mathematician, believed that the commonly accepted knowledge would be doubtful because of the subjective nature of human senses. He attempted to rebuild human knowledge structure by using the fundamental concept known as 'cogito ergo sum' (*I think, therefore I am*). Descartes said,

> If you would be a real seeker after truth, it is necessary that at least once in your life you doubt, as far as possible, all things.

The author perceives that human beings are living in two worlds. One is the physical or the concrete world; the other is the abstract or the perceived world. We use *matter* and *energy* to model the former, and *information* to the latter. An information–matter–energy (I-M-E) model, as shown in Figure 1, is developed to describe the generic view towards the physical and information worlds that we are living and doing research.

Models of the natural world have been well studied in physics and other natural sciences. Relationships between matter and energy have been investigated and revealed by Einstein and other scientists. However, the modeling of the abstract world is still a fundamental issue yet to be explored, in informatics, computing, software, cognitive science, life sciences, and philosophy. Especially, the relationships between I-M-E and their transformations are perceived as one of the fundamental questions in CI (Wang, 2001, 2002a). It is believed

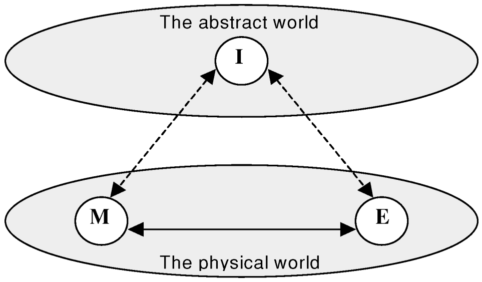

Figure 1. The I-M-E model of the world view.

that any breakthrough in this area, known as CI, will be profoundly significant towards the development of the next generation technologies in informatics, computing, software, and cognitive sciences.

The brain is perhaps the last thing in the natural world yet to be explored and understood. One of the most interesting findings in cognitive informatics is that so many science and engineering disciplines, such as informatics, computing, software engineering, and cognitive sciences, share a common root problem – how the natural intelligence processes information.

Along with the development of natural sciences, particularly psychology, cognitive science, and cognitive informatics, there are a number of significant scientific discoveries that shed light on the nature of human beings and in the same time blow on human self-esteem (Leahey, 1980):

- *The first blow:* Nicholas Copernicus (1473–1543) – Human beings did not live at the center of the universe.
- *The second blow:* Charles Darwin (1809–1882) – Human beings were part of nature – being animals like any other.

The author's explanation of Darwin's finding from the viewpoint of CI is that the human brain at the basic level has no difference from other animals; while it possesses (a) the quantitative advantage – the magnitude of the memory capacity of human brains is tremendously large than that of the most close species and (b) the qualitative advantages – the abstract layer of human memory and the abstract reasoning capacity of the human brain makes it profoundly powerful on the basis of the quantitative advantage (Wang and Wang, 2002; Wang *et al.*, 2003).

- *The third blow:* Sigmund Freud (1856–1939) – The human ego is not master in its own house, since many human behaviors are determined by nonconscious life functions.

Although Freud's theory indicates that many fundamental human behaviors are nonconscious and there was no direct access and control by the conscious life functions, psychology and cognitive science still maintain a common belief that an individual human being is at least autonomous and behaves purely on own desires and motivations. However, this assertion may be doubt in cognitive informatics.

- *The possible fourth blow*: Yingxu Wang – Human beings do not behave autonomously as believed. According to the cognitive informatics theory (Wang, 2001, 2002a; Wang *et al.*, 2002), human behaviors are determined by external events and conditions in terms of event-, time-, and willingness-driven mechanisms.

The basic life function of the human brain is information processing. Although the brain may be stimulated by both external information and internal information, the internal information is previously acquired from external sources. The willingness-driven mechanism of human behaviors was thought be purely determined by internal information and conditions such as goals, desires, and emotions. On the basis of this perception, an individual person may be considered as an autonomous human being. However, by considering the sequential logic principles developed in CI and computing, all willingness-driven behaviors, the non-conscious or subconscious life functions as identified by Freud, are synthetically dependent on the historical external events, information, status, and current internal physiological and subconscious conditions. That is, the universal causality in the study of human brains and cognitive behaviors can still be preserved, even some of the willingness-driven cause–effects are not so direct due to long-term and indirect feedback in the human memory (Wang and Wang, 2002; Wang *et al.*, 2003).

The willingness-, event-, and time-driven life functions and their cognitive processes may be formally described by Real-Time Process Algebra (RTPA) (Wang, 2002c; Wang *et al.*, 2002; Wang, 2003), which provides an expressive mathematics means for rigorously describing the meta-cognitive life functions such as abstraction, search, sort, and remember; and higher cognitive life functions such as recognition, imagination, comprehension, reasoning, learning, thinking, and problem solving.

This paper attempts to describe the historical development of informatics from the classical information theory, to contemporary informatics, and then to cognitive informatics. Section 2 reviews the classical information theory and their impacts on communication and information transmission techniques. Section 3 describes the contemporary informatics developed in the last few decades. Section 4 addresses the implication and extension of CI, and its domains of study and applications. The foundations of CI and their potential impacts will be explored in Section 5.

2. The Classical Informatics

The classical information theory is commonly regarded to be founded by *Shannon* during 1948–49 (Shannon, 1948; Shannon and Weaver, 1949), while the term *information* was first adopted by Hartley in 1928 (Hartley, 1928), and extensively discussed by Bell and Goldman in 1953 (Bell, 1953; Goldman, 1953). In the classical information theory, Shannon defined *information* as a probabilistic measure of the variability of message which can be obtained from a message source (Shannon, 1948). Conventional information theory was modeled on the basis of probability theory, and focused on information transmission rather than on information itself.

2.1. INFORMATION AND ITS MEASUREMENT

In the early 1940s, it was thought that increasing the transmission rate of information over a communication channel increased the probability of error. Shannon surprised the communication theory community by proving that this was not true as long as the communication rate was below the channel capacity. The capacity can be simply computed from the noise characteristics of the channel.

The classical information theory was probability-based. It defines information as follows.

Definition 1. *Information* is a weighted probabilistic measure of the variability of messages (signals) that is expected from message sources via a transmission channel.

The information variability, I_i, of the ith sign in a message is determined by its unexpectedness, i.e.,

$$I_i = \log_2(1/p_i) \quad \text{[bit]} \tag{1}$$

where p_i is the probability that the ith sign is transmitted. The unit of information is *bit*, shortened from 'binary digit.'

The total information variability transmitted by a source or sender, I, is the weighted sum of probability of its n possible signs in the message (Shannon, 1948), i.e.,

$$I = \sum_{i=1}^{n} p_i \cdot I_i = \sum_{i=1}^{n} p_i \cdot \log_2(1/p_i) = -\sum_{i=1}^{n} p_i \cdot \log_2 p_i \quad \text{[bit]} \tag{2}$$

For example, for a binary source that has an alphabet of two equally likely signs, or $p_i = 0.5$, its information variability, I, is

$$I = \sum_{i=1}^{2} p_i \cdot \log_2(1/p_i) = \sum_{i=1}^{2} 0.5 \cdot \log_2(1/0.5) = 1 \quad \text{[bit]} \tag{3}$$

It is noteworthy that for the above binary system, the information variability is always 1 bit. In other words, I is a measure of information variability rather than that of information quantity. Therefore, I is not proportional to the sizes of messages, according to Eq. 2. On the basis of the classical information measurement, no matter how many bits message have been transmitted, the value of I will not change for a given transmission system. This result may be surprisingly contradictory to the common understanding of information in contemporary informatics and in the information technology (IT) industry.

Another important concept in the classical information theory is entropy (Shannon, 1948; Bell, 1953; Goldman, 1953). *Entropy* is the extent of the trend of a system towards complete disorder or randomization. The *quantity of entropy* of a source is defined as its total weighted information variability transmitted by the source as described by Eq. (2). The maximum entropy for a source occurs if the probabilities of all signals are equal (Shannon, 1948). In physical systems, entropy can be reserved by inputs of *energy* to achieve an increased order and organization. While in neural and social systems, order and the state of organization may be increased by inputting information.

2.2. DOMAIN OF CLASSICAL INFORMATION THEORY

The domain of the classical information theory encompasses communication and coding theories. The former studies models of communication channels, noises, and signal processing. The latter deals with data encoding, decoding, compression, protection, and encryption.

The classical information theory answers two fundamental questions in the communication theory: (a) What is the ultimate transmission rate of communication and (b) what is the maximum rate of data compression? For the former, Shannon revealed that the ultimate transmission rate of a channel is the maximum channel capacity. For the latter, Shannon answered that the maximum data compression rate is the entropy (information) of the data (Shannon, 1948).

In addition to being the foundation of communication theory, the classical information theory has also found a wide range of applications in algorithm complexity analysis in computer science, functional and information sizes measurement in software engineering, and statistical mechanisms in physics.

A dilemma in the classical information theory is that the measurement of the quantity of information is dependent on the receiver's subjective judgment. According to the classical information theory, information is the message that one does not expect and know. Therefore, a subjective criterion has been introduced into the objective measurement of information. This results in that the same message represents varying information for different observers depending on their degrees of awareness of the message. Further, every time whenever one reads the same message, the information that one may obtain decays all the time because of the loss of uncertainty.

The conventional information theory was used to study models of communication channels and coding/decoding systems. Alternative information theories have been developed in the last decades to extend the usage of classical informatics, such as the non-probability-based theory, unknown-probability channel theory, decision theory, and belief theory.

3. Contemporary Informatics

As discussed in Section 2, conventional informatics treats *information* as a probabilistic measure of the variability or uncertainty of messages that can be received from a source. It was focused on information transmission rather than on information itself.

The domain of informatics has been extended in the last decades along with the development in computer science and in the IT industry. The modern informatics tends to regard information as entities of messages, rather than as a probabilistic measurement of the variability of messages as that of the classical information theory. The new perception is found better to explain the theories in computer science and practices in the IT industry.

3.1. MODERN PERCEPTION ON INFORMATION

It is observed that in applied computer and software sciences and in the IT industries, the term *information* has a much more practical and concrete meaning that focuses on data and knowledge representation, storage, and processing. With this orientation, information is regarded as an entity of messages, rather than as a measurement or metric of the messages' variability. With this perspective, the definition of *information* has been shifted from the classical informatics to the contemporary informatics as follows.

Definition 2. *Information* in modern informatics is defined as any property or attribute of the natural world that can be generally abstracted, quantitatively represented, and mentally processed (Wang, 2001, 2002a).

From Definition 2 it can be seen that the implication and extension of information has been shifted from probability of messages to organized data that represents the messages, knowledge, and/or abstracted real-world entities. With this new orientation, information is regarded as an independent and essential entity in modeling the natural world, particularly its abstract part.

Definition 3. The *content of information* in modern informatics is measured by the cost of code to abstractly represent a given size of message M in a digital system based on k (Wang, 2002), i.e.,

$$I_k = f : M \to S_k = \log_k M \tag{4}$$

where I_k is the content of information in a k-based digital system, and S_k the measurement scale based on k. The unit of I_k is the number of k-based digits.

Equation (3) is a generic information size measurement. When a binary digital representation system is adopted, i.e., $k = b = 2$, it becomes the most practical one:

$$I_b = f : M \to S_b = \log_2 M \quad [\text{bit}] \tag{5}$$

where the unit of information, I_b, is a *bit*. Note that the bit here is concrete and deterministic, and it no longer possesses a property as a value of weighted probability as that in Eq. (2). According to Eq. (4), for given messages $\mathrm{M}_1 = 2$ bits and $M_2 = 2^{30}$ bits, their information contents can be determined respectively as follows:

$$I_{b1} = \log_2 M_1 \tag{6}$$

$$= \log_2 2 \tag{7}$$

$$= 1 \quad [\text{bit}] \tag{8}$$

and

$$I_{b2} = \log_2 M_2 \tag{9}$$

$$= \log_2 2^{30} \tag{10}$$

$$= 30 \quad [\text{bit}] \tag{11}$$

The results show that messages M_1 and M_2 contain, respectively, 1 bit and 30 bits information. In the other word, information $I_{b1} = 1$ bit and $I_{b1} = 30$ bits may represent messages in sizes of 2 or 2^{30} bits respectively.

With the new perception on information according to Definitions 2 and 3, it is natural and intuitive to perceive IT as any technology that can be used for the processing of information. In the same way, an information system can be defined as an abstract representation system for information elicitation, acquisition, storage, manipulation (adding, deleting, updating), production, presentation, searching, and retrieving.

3.2. PROPERTIES OF INFORMATION

In Section 1, information, matter, and energy have been identified as the three fundamental essences of the world. According to the I-M-E model, as shown in Figure 1, information plays a vital role in connecting the natural world and the abstract world. A set of 12 properties of information and laws of informatics has been developed by Wang *et al.* (2001) and Wang (2002b) as shown below:

(1) Abstract artifacts
(2) Cumulativeness
(3) Lossless reusable
(4) Dimensionless
(5) Weightless
(6) Transformability between I-M-E
(7) Multiple representation forms
(8) Multiple carrying media
(9) Multiple transmission forms
(10) Generality of sources
(11) Conservation of information entropy and thermal entropy
(12) Different quality attributes from physical entities and products

From the above list, it can be seen that informatics is a unique discipline in the human knowledge structure. According to the natural law of conservation, matter can be neither reproduced nor destroyed. However, contrasting to the properties of matter, important attributes of information are that it can be reproduced, destroyed, and accumulated. The accumulative capability of information is the most significant attribute of information that the mankind relies on for evolution.

Further description of the above properties of information can be found in the literature (Wang *et al.*, 2001; Wang *et al.*, 2002b). The properties and laws of information are helpful to explain the nature of information science and the IT technology, which are tackling a wide range of fundamental problems in the interdisciplinary area between conventional natural sciences and modern informatics-based sciences, particularly, in the area of computing and software engineering.

4. Cognitive Informatics

Stillings *et al.* assumed that “the human mind is a complex system that receives, stores, retrieves, transformes, and transmits information” (Stillings and Feinstein, 1987). According to the I-M-E model, the information theories discussed in Sections 2 and 3 can be classified as the *external* informatics. Complementary to it, there is a whole range of new research areas known as CI that focuses on the internal information processing of the brain (Stillings and Feinstein, 1987; Wang, 2001, 2002b; Wang *et al.*, 2001; Wang and Wang, 2002).

Harre perceived that cognitive science is the study of cognitive phenomena (Wilson and Frank, 1999; Harre, 2002). Dawson considered "the central assumption for cognitive science is information processing" (Dawson, 1998). Therefore, cognitive science is the study of the brain, the mind, and intelligent behavior that blends anthropology, computer science, psychology, neuroscience, linguistics, sociology, and philosophy.

CI is a cutting-edge and interdisciplinary research area that tackles the common root problems of modern informatics, computing, software engineering, AI, cognitive science, and neuropsychology. This section explores fundamentals of cognitive informatics and its potential impacts on, and applications in, information-based sciences and engineering disciplines.

4.1. EXTERNAL VS. INTERNAL INFORMATICS

CI is a new transdisciplinary research area that encompasses informatics, computer science, software engineering, mathematics, knowledge theory, cognition science, neurobiology, psychology, and physiology.

Definition 4. *Cognitive informatics* is the transdisciplinary study of cognitive and information sciences that investigate into the internal information processing mechanisms and processes of the natural intelligence – human brains and minds.

CI attempts to solve problems in two connected areas in a bidirectional and multidisciplinary approach. In one direction, CI uses cognitive science theories to investigate informatics, computing, and software engineering problems, such as information and knowledge representation in the brain, the nature of computing, cognitive complexity of software, abstraction of software, and system behaviors. In the other direction, CI uses computing theories to investigate cognitive science problems, such as memory, learning, and thinking.

The relationship between the internal and external informatics can be illustrated in Figure 2. In CI, the brain is perceived as the last thing in the world yet to be explored. To explore it, special recursive research power of human beings is required. This makes cognitive informatics unique in distinguishing from other natural sciences.

CI focuses on the nature of information in the brain, such as information acquisition, memory, categorization, retrieve, generation, representation, and communication. Via an interdisciplinary approach and with the support of modern information and neural science technologies, mechanisms of the brain and the mind will be systematically explored in CI.

Definition 5. *Information* in cognitive informatics is defined as abstract artifacts and their relations that can be modeled, processed, stored, and processed by human brains. The measurement of information in cognitive informatics is the same as defined in Definition 3 (Wang, 2001).

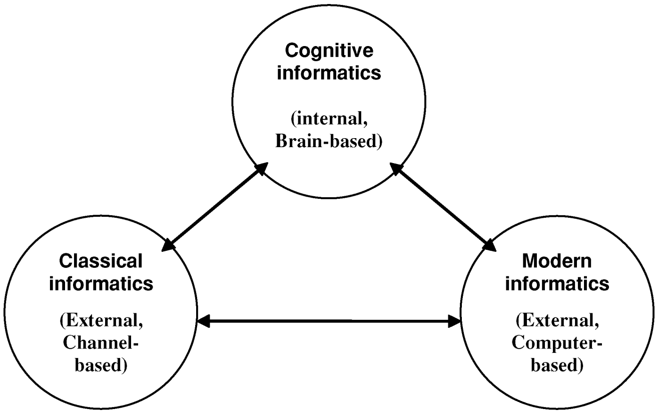

Figure 2. Relationship between cognitive informatics and existing informatics.

It is recognized that at the fundamental level, the brain models information by only four meta types (Wang and Wang, 2002): *object*, *attribute*, *relation*, and *action*, as shown in Table I. However, the magnitude of connections among them is extremely high, which can be at the order of 10^{8432} bits according to a recent study (Wang and Wang, 2002; Wang *et al.*, 2003). On the basis of this observation, an object–attribute–relation (OAR) model of human memory is developed in the literature (Wang and Wang, 2002), which presents a generic memory model of the brain. Further investigation into models of the brain and cognitive mechanisms of the mind will be one of the focuses in CI.

4.2. DOMAIN OF COGNITIVE INFORMATICS

CI covers a whole range of interdisciplinary research in subject areas including, inter alia, the following:

- Intellectual foundations of informatics
- Internal information processing mechanisms

Table I. The meta-cognitive models of the brain

Cognitive Models	Description	Mathematical Abstraction
Object	The abstraction of external entities and internal artifacts	Set, tuple
Attribute	Detailed properties and characteristics of an object	Set, tuple
Relation	Connections and relationships between object–object, object–attributes, and attribute–attribute	Relational algebra, combinational logic
Action	A sequence of state transitions of sensors and motor muscles	Process algebra, automata

- Memory models of the brain
- Cognitive models of the mind
- Descriptive mathematics
- Semantic nets
- Intellectual roots of computing
- Cognitive foundations of software engineering
- Informatics laws of software
- Knowledge representation
- Extension of human memories
- New approaches to computing
- Applications in informatics
- Applications in cognitive science

According to the I-M-E model, as shown in Figure 1, the three basic essences of the world are predicated to be transformable between each other. Figure 1 demonstrates that there are six possible relations between the three essences of the natural and information worlds. They can be described by the following generic functions f_1 to f_6:

$$I = f_1(M) \tag{5a}$$

$$I = f_2(E) \tag{5b}$$

$$M = f_3(I) \tag{5c}$$

$$M = f_4(E) \tag{5d}$$

$$E = f_5(I) \tag{5e}$$

$$E = f_6(M) \tag{5f}$$

Albert Einstein has revealed function f_6, the relationship between matter (M) and energy (E), in the form of $E = mC^2$. It will be interesting to expect what the remaining relationships and forms of transformations between I-M-E are. In this case, CI, in a certain extent, is the science to seek possible solutions for f_1 to f_6. A clue to explore the relations and transformability between I-M-E is believed in the understanding of the natural intelligence and its information processing mechanisms in the emerging area of CI.

The applications of CI in cognitive science will cover a wide range of cognitive phenomena, as shown in Table II, at the sensation, subconscious, meta-cognitive, and higher cognitive function levels.

The applications of CI in informatics, computer science, and software engineering are potential in the following areas:

- Nature of software
- Software engineering methodologies
- Artificial intelligence
- Knowledge representation
- Knowledge engineering

Table II. Classification of cognitive phenomena

Subconscious Functions		Conscious Functions	
Level 0 (Sensation)	Level 1 (Subconscious Life Functions)	Level 2 (Meta-Cognitive Functions)	Level 3 (Higher Cognitive Functions)
Vision	Maintaining consciousness conditions	Abstraction	Recognition
Audition	Memory	Search	Imagination
Smell	Desires	Sort	Comprehension
Touch	Feeling	Remember	Reasoning
Thermal	Personality	Knowledge	Correlation
Pressure			Learning
Weight			Thinking
Texture			Mathematical operations
Tastes			Induction
Sweet			Deduction
Bitter			Determination
Sour			Summarization
Salt			Invention
Pungency			Problem solving

- Bioinformatics
- Quantum information processing
- Fuzzy logic
- Machine learning
- Neural networks
- Pattern recognition
- Agent technologies
- Generic algorithms
- Information systems modeling
- Web-based information systems

Therefore, the interdisciplinary nature of CI will benefit not only conventional informatics and computing research by understanding the natural intelligence and its mechanisms, but also cognitive and life sciences by informatics theories and formal methods.

5. Foundations of Cognitive Informatics

Based on the exploration of the domain of cognitive informatics in Section 4, this section investigates the foundations of CI.

5.1. A MULTIDISCIPLINARY AREA

CI is a discipline that forges links between a number of natural science and life science disciplines with informatics and computing science. The relationship between CI and other natural sciences can be perceived as shown in Figure 3.

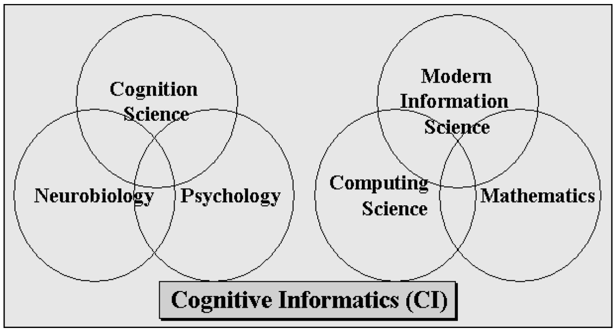

Figure 3. Relationship between cognitive informatics and natural sciences.

The foundations of CI can be classified into three categories as shown in Table III.

According to CI, the cognitive information and knowledge modeled in the brain can be divided into different abstraction levels, such as analogue objects, natural languages, professional notation systems, mathematics, and philosophies. A classification of the cognitive abstract levels is shown in Table IV.

Table IV is useful to identify if a given object can be categorized as a type of information in the abstract world or a type of entity in the physical world. For example, the nature of software has been argued since the emerging of the first generation computers in the 1940s. Is software a physical entity or a type of information? According to the classification of the abstract levels of cognitive information in Table IV, it can be seen that software is certainly a kind of information at the abstract levels 3 or 4, rather than a physical entity.

5.2. THE BRAIN AND THE MIND

The brain is an information processing organ of human beings and a real-time controller of the body. The mind is an abstract model of oneself and a thinking engine. The relationship between the brain and the mind can be analogized by

Table III. Foundations of cognitive informatics

Category	Category of Sciences	Discipline of Sciences
1	Informatics	
1.1		Modern informatics
1.2		Computing theory
1.3		Software science
1.4		Artificial intelligence
2	Natural sciences	
2.1		Cognitive science
2.2		Neurobiology
2.3		Psychology
2.4		Physiology
2.5		Mathematics
3	Humanity	
3.1		Philosophy
3.2		Linguistics

Table IV. Abstract levels of cognitive information

Level	Category	Description
1	Analogue objects	Real-world entities, empirical artifacts
2	Natural languages	Empirical methods, heuristic rules
3	Special notation systems	Professional languages, formal methods
4	Mathematics	High-level abstraction of objects, attributes, and their relations and rules, particularly those that are time and space independent
4.1	Formulae	Mathematical description of relations or rules
4.2	Theorems	Proved relations or rules
4.3	Corollaries	Derived relations and rules based on known theorems
5	Philosophies	The highest-order abstraction of generic objects and their relations and rules, particular those that are time- and space-independent

$$\text{Brain} : \text{Mind} = \text{Computer} : \text{Program} \tag{6}$$

The existence of the virtual model of human beings, the mind, can be proven by the following mental phenomena: (a) If you close your eyes, you may still imagine or 'see' everything you learned and remembered, particularly, the visual information, such as the hands and a pen; and (b) it is reported that patients who lost a leg or an arm may think or feel, from time to time, that they still have it as before, because the original cognitive model about the organ at the lower layer of the brain may not be eliminated, rather than override or patched at a higher layer, whenever it had been physiologically created.

The mind, as a virtual model of a person in the brain, is partially programmed and partially wired. The former is evolved for the flexibility of life functions, while the latter is formed for the efficiency of frequently conducted activities, such as eating, writing, and driving.

5.3. NI-OS AND NI-APP

CI studies the brain as a real-time natural intelligent (NI) information processing system, NI-Sys (Wang and Wang, 2002), which is configured by a predetermined operating system (the thinking engine) NI-OS and a set of acquired life applications NI-App, i.e.,

$$\begin{aligned}\text{NI-Sys} \triangleq\ & \text{NI-OS} \\ & \| \text{NI-App}\end{aligned} \tag{7}$$

where, NI-OS represents the inherited life functions, NI-App the developed or acquired life functions, and $\|$ a parallel relation.

A hierarchical structure of NI-Sys can be illustrated in Figure 4, which functions as a set of parallel interactions between NI-OS and NI-App. NI-Sys can respond to internal and external information in event-driven, time-driven, and desire-driven approaches.

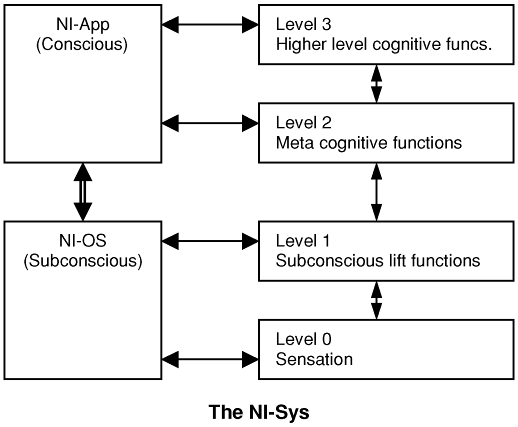

Figure 4. Relationship between NI-OS and NI-App.

Corresponding to Table II, the Level 0 and Level 1 life functions in Figure 4 belong to NI-OS, and the Level 2 and Level 3 life functions are a part of NI-App.

The characteristics of NI-OS have been observed as follows:

- Inherited
- Wired (by neural networks)
- A real-time system
- Running subconsciously and automatically
- Person-independent, common and similar
- Highly parallel and fault-tolerant
- Use event-/time-/willingness-driven mechanisms
- A born visual processor

In contradiction, the characteristics of NI-App have been identified below:

- Acquired
- Partially wired (frequently used functions) and partially programmed (temporary functions)
- Running consciously
- Person-specific
- Can be trained and programmed
- Use event-/time-/willingness-driven mechanisms
- A trained notation processor

Unlike a computer, the brain works in two approaches: the internal *willingness-driven* processes (in NI-OS), and the external *event*- and *time-driven* processes (in NI-App). The external information and events are the major sources that stimulate the brain, particularly for NI-App functions. In this case, the brain may be perceived as a passive system, at least when it is conscious, which is controlled and driven by external information. Even the internal willingness, such as goals, desires, and emotions, may be considered as derived information based on originally external information. This is a fundamental view towards the mechanisms of the brain in cognitive informatics.

6. Conclusions and Perspectives

CI has been recognized as a new frontier that studies internal information processing mechanisms and processes of the brain, and their applications in computing and the IT industry. CI has been described as a profound interdisciplinary research area that tackles the common root problems of modern informatics, computation, software engineering, AI, cognitive science, nueropsychology, and life sciences.

The development of informatics from the classical information theory, contemporary informatics, to CI has been reviewed. On the basis of this, the foundations of cognitive informatics and its potential applications have been explored. This paper has demonstrated that the brain is the last thing in the world yet to be studied, and CI is a special area that requires recursive research power of human beings. The exploration and unveiling of relationships and ways of transformation between information, matter, and energy, the three essences of the world, will be one of the potential breakthrough-making areas in CI.

Major problems yet to be solved in CI are such as the architectures of the brain, mechanisms of the natural intelligence, cognitive processes, mental phenomena, and personality. It is particularly interested in computing and software engineering to explain the mechanisms and processes of memory, learning and thinking. It is expected that any breakthrough in CI will be profoundly significant towards the development of the next generation technologies in informatics, computing, software, and cognitive sciences.

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Author's queries:

A1: Au: Kindly provide the state name.
A2: Au: Kindly provide the state name.
A3: Au: Kindly provide the state name.