Contemporary Cybernetics and Its Facets of Cognitive Informatics and Computational Intelligence

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***Abstract*—This paper explores the architecture, theoretical foundations, and paradigms of contemporary cybernetics from perspectives of cognitive informatics (CI) and computational intelligence. The modern domain and the hierarchical behavioral model of cybernetics are elaborated at the imperative, autonomic, and cognitive layers. The CI facet of cybernetics is presented, which explains how the brain may be mimicked in cybernetics via CI and neural informatics. The computational intelligence facet is described with a generic intelligence model of cybernetics. The compatibility between natural and cybernetic intelligence is analyzed. A coherent framework of contemporary cybernetics is presented toward the development of transdisciplinary theories and applications in cybernetics, CI, and computational intelligence.**

***Index Terms*—Autonomic systems, behavioral models, cognitive informatics, cognitive models, cognitive systems, computational intelligence, cybernetics, imperative systems, machine intelligence, mathematical models, natural intelligence.**

I. INTRODUCTION

CYBERNETICS is the science of communication and autonomous control in both machines and living things as proposed by Norbert Wiener in 1948. In his work on *Cybernetics or Control and Communication in the Animal and the Machine* [57], Wiener initiated the field of cybernetics to provide a mathematical means for studying adaptive and autonomous systems. Cybernetics mimics information communicated in machines with that of the brain and nervous systems. It also attempts to elaborate human behavior by cybernetic engineering concepts [3], [4], [13], [21], [29], [51], [58]. Cybernetics constitutes one of the roots of modern cognitive science.

The history of cybernetics can be traced back to the works of Wiener, von Neumann, Turing, and Shannon as early as in the 1940s [36], [39], [41]–[43], [57], [58]. In the same period, McCarthy *et al.* proposed the term *artificial intelligence* (AI) [30], [32]. Kleene analyzed the relations of automata and nerve nets [26], and Widrow and Lehr initiated the technology of *artificial neural networks* in the 1950s [59] based on multilevel, distributed, dynamic, interactive, and self-organizing nonlinear networks [1], [8], [12]. The concepts of robotics [6] and expert systems [11] were developed in the 1970s and 1980s, respectively. Then, intelligent systems [33] and software agents [14], [17] emerged in the 1990s. These events and developments lead to the development of contemporary cybernetics.

It was conventionally deemed that only human beings and other advanced species possess intelligence. However, the development of computers, robots, and cybernetic systems indicates that intelligence may also be created or implemented by machines and man-made systems. Therefore, it is one of the key objectives in cybernetics to seek a coherent theory for explaining the mechanisms of both natural and machine (artificial) intelligence [4], [44], [57], [58].

The history of investigation into the brain and natural intelligence (NI) is as long as the history of mankind. Early studies on cybernetics and NI are represented by works of Vygotsky, Spearman, and Thurstone [60]. Lev Vygotsky (1896–1934) presented a communication view that perceives intelligence as an inter- and intrapersonal communication in a social context. Charles E. Spearman (1863–1945) and Lois L. Thurstone (1887–1955) proposed the *factor theory* [27], in which seven factors of intelligence are identified such as the *verbal comprehension*, *word fluency*, *number facility*, *spatial visualization*, *associative memory*, *perceptual speed*, and *reasoning*. Jensen's *two-level theory* [18]–[20] classified intelligence into the *associative* and *cognitive* ability levels. The former is the ability to process external stimuli and events, while the latter is the ability to carry out reasoning and problem solving. Gardner's *multiple intelligence theory* [10] identified eight forms of intelligence, which are those of *linguistic, logical–mathematical*, *musical*, *spatial*, *bodily kinesthetic*, *naturalist*, *interpersonal*, and *intrapersonal*. He perceived that intelligence is an ability to solve a problem or create a product within a specific cultural setting.

In the turn of the new century, Sternberg's *triarchic theory* [38] modeled intelligence in three dimensions known as the *analytic*, *practical*, and *creative* intelligence. He perceived intelligence as the ability to adapt, shape, and select environments

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to accomplish one's goals and those of society. Lefton *et al.* [27] defined intelligence as the overall capacity of the individual to act purposefully, to think rationally, and to deal effectively with the social and cultural environment. They perceived that intelligence is not a thing, but a process that is affected by a person's experiences in the environment. Wang's *abstract intelligent theory* (αI) [44], [51] revealed that NI is the driving force that transforms cognitive information in the forms of data, knowledge, skill, and behavior. A *Layered Reference Model of the Brain* (LRMB) has been developed [52], which encompasses 43 cognitive processes at seven layers known as the *sensation*, *memory*, *perception*, *action*, *metacognitive*, *metainference*, and *higher cognitive layers* from the bottom up.

The development of classic and contemporary cybernetics, cognitive informatics (CI), and the cross fertilization between computer science, system science, computer/software engineering, neuropsychology, and computational intelligence have led to a wide range of interesting new research fields known as CI [44], [45], [47], [49], [51], [54], [55]. CI is an interdisciplinary research field that tackles the fundamental problems of modern cybernetics, information science, systems science, computer/software engineering, computational intelligence, cognitive science, neuropsychology, and life sciences. Almost all of the hard problems yet to be solved in the aforementioned areas share a common root in the understanding of the mechanisms of the NI and cognitive processes of the brain. Therefore, CI is perceived as a new frontier that explores the internal information processing mechanisms of the brain and their engineering applications in cybernetics, computing, and information technology industry.

This paper attempts to explore the theoretical foundations and engineering paradigms of contemporary cybernetics, particularly its newly developed facets known as CI and computational intelligence. In the remainder of this paper, the contemporary architecture of cybernetics and its hierarchical behavior model at the imperative, autonomic, and cognitive layers are elaborated in Section II. The CI facet of cybernetics is presented in Section III, which explains how the brain may be mimicked in cybernetics via CI. The computational intelligence facet of cybernetics is described in Section IV, which presents the generic intelligence model (GIM) of cybernetics and analyzes the compatibility between the natural and cybernetic intelligence. As a result, a coherent framework of contemporary cybernetics is elaborated toward the development of interdisciplinary and transdisciplinary theories and application paradigms in cybernetics, CI, and computational intelligence.

II. CONTEMPORARY ARCHITECTURE OF CYBERNETICS

Studies in cybernetics cover biologically, cognitively, and intelligently motivated computational paradigms [5], [15], [21], [31], [40], [51] such as abstract intelligence, neural networks, genetic algorithms, fuzzy systems, autonomic systems, cognitive systems, robotics, CI, and computational intelligence.

Definition 1: Cybernetics is the science of communication and control in humans, machines, organizations, and societies across the reductive hierarchy of neural, cognitive, functional, and logical levels.

A. Domain of Cybernetics

The domain and architecture of contemporary cybernetics encompass a wide range of coherent fields, as shown in Fig. 1, from the machine, natural, and organizational intelligence to social intelligence in the horizontal scopes and from the logical, functional, and cognitive models to neural (biological) models in the vertical reductive hierarchy. Therefore, cybernetics in nature is a multidisciplinary and transdisciplinary inquiry of cognitive information processing and autonomic systems.

As shown in Fig. 1, the double arrows indicate abstraction/reduction or aggregation/specification. The scope of contemporary cybernetics in the horizontal domains has been extended from mainly machine intelligence to natural, organizational, and societal intelligence. In the vertical dimension, the reduction levels of cybernetics have been extended from logical and functional models to cognitive and neural models.

With the notion of *functional reductionism*, a logical model of the NI is needed to explain formally the high-level mechanisms of the brain on the basis of observations at the biological and physiological levels. The logical model of the brain is the highest level of abstraction for explaining its cognitive mechanisms. Based on it, a systematical reduction from the logical, functional, physiological, and biological levels may be established in both the top–down and bottom–up approaches, which will enable the establishment of a coherent theory of NI and cybernetics.

It is noteworthy that, at the overall level, contemporary cybernetics has evolved from pure autonomic communication and control theories to CI [44], [45] and computational intelligence [22]. The former provides an extended NI and internal information-processing perspective to cybernetics, while the latter studies a computation modeling perspective to cybernetics.

B. Behavioral Spaces of Cybernetics

Behaviorism is a doctrine of psychology and CI that studies the association between a given stimulus and an observed response of human brains and cybernetic systems [45], [52]. CI reveals that human and machine behaviors may be classified into four categories known as the *perceptive*, *cognitive*, *instructive*, and *reflective* behaviors [46].

The behavioral space of cybernetics and cybernetic systems can be classified into the imperative, autonomic, and cognitive cyberspaces (CSs), as shown in Fig. 2. The *imperative CS* is an enclosure of instructive and passive behaviors. The *autonomic CS* is an enclosure of internally motivated behaviors beyond those of the imperative space. The *cognitive CS* is an enclosure of perceptive and inference-driven behaviors beyond those of both imperative and autonomic spaces. More formal descriptions of the three forms of CSs will be presented in Section II-B2, after each layer of the hierarchical CSs and their basic properties is formally modeled as follows.

1) Behavioral Models of Cybernetics: Before the elaboration of the behavioral spaces of cybernetics, the taxonomies of cybernetic behaviors at different layers of cybernetics, as shown in Fig. 2, are formally modeled in the following.

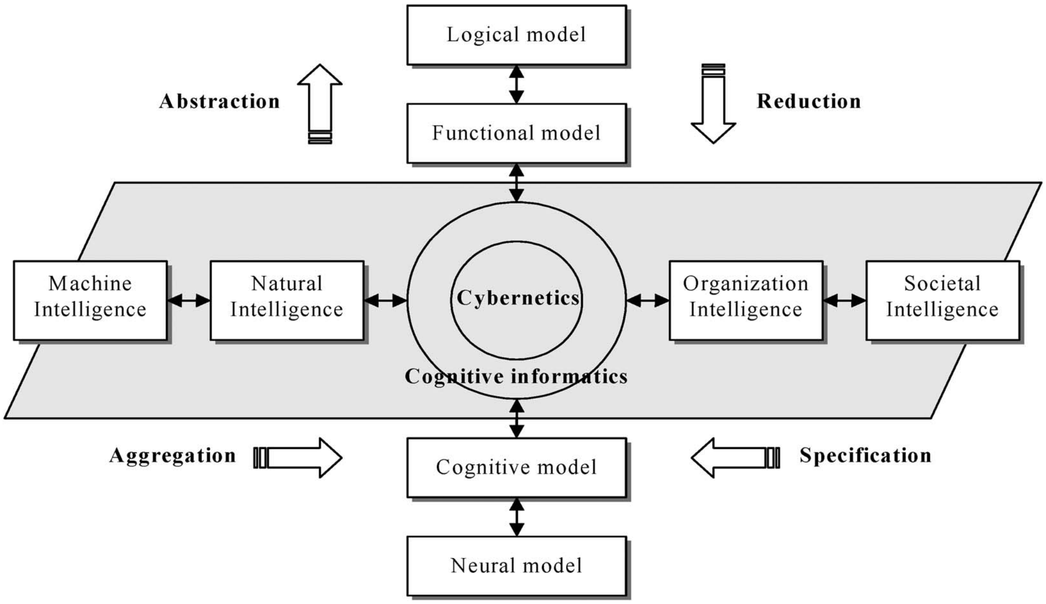


Fig. 1. Architecture of contemporary cybernetics and CI.

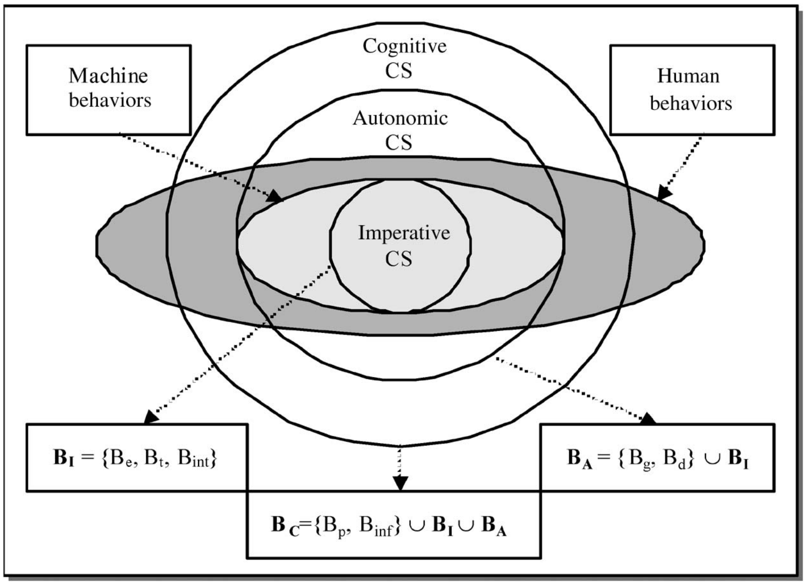


Fig. 2. Behavioral spaces of cybernetics.

Definition 2: An *event* is an abstract variable that represents an external stimulus to a system or the occurrence of an internal change of status, such as an action of users, an updating of the environment, and a change of the value of a control variable.

The types of events that may trigger a behavior can be classified into operational ($@e\mathbf{S}$), time ($@t\mathbf{TM}$), and interrupt ($@int\odot$) events, where @ is the *event prefix*, and $\mathbf{S}$, $\mathbf{TM}$, and $\odot$ are three of the type suffixes, respectively. The *interrupt event* is a kind of special event that models the interruption of an executing process, the temporal handover of controls to an interrupt service routine, and the return of control after its completion.

Definition 3: An *interrupt*, which is denoted by $\lightning$, is a parallel process relation in which a running process P is temporarily held by another higher-priority process Q via an interrupt event ($@int\odot$) at the interrupt point $\odot$, and the interrupted process will be resumed when the high-priority process has been completed, i.e.,

$$P \lightning Q \triangleq P \parallel (@int\odot \nearrow Q \searrow \odot) \tag{1}$$

where $\nearrow$ and $\searrow$ denote an *interrupt service* and an *interrupt return*, respectively.

In general, all types of events, including the operational, timing, and interrupt events, are captured by the system to dispatch a designated behavior.

Definition 4: An *event-driven behavior* B_e, which is denoted by $\hookrightarrow_e$, is an imperative process in which the ith behavior in terms of a designated process P_i is triggered by a predefined event $@e_i\mathbf{S}$, i.e.,

$$B_e \triangleq \mathop{\mathrm{R}}\limits_{i=1}^{n} (@e_i\mathbf{S} \hookrightarrow_e P_i) \tag{2}$$

where the big-R notation is a mathematical calculus that denotes a sequence of repetitive/iterative behaviors or a set of recurring structures [46].

Definition 5: A *time-driven behavior* B_t, which is denoted by $\hookrightarrow_t$, is an imperative process in which the ith behavior in terms of process P_i is triggered by a predefined point of time $@t_i\mathbf{TM}$, i.e.,

$$B_t \stackrel{\triangle}{=} \overset{n}{\underset{i=1}{\mathrm{R}}}(@t_i\mathbf{TM}\hookrightarrow_t P_i) \tag{3}$$

where $@t_i\mathbf{TM}$ may be a system timing or an external timing event.

Definition 6: An *interrupt-driven behavior* B_{int}, which is denoted by $\hookrightarrow_{\mathrm{int}}$, is an imperative process in which the ith behavior in terms of process P_i is triggered by a predefined system interrupt $(@int\odot)$, i.e.,

$$B_{\mathrm{int}} \stackrel{\triangle}{=} \overset{n}{\underset{i=1}{\mathrm{R}}}(@int_i\odot\hookrightarrow_{\mathrm{int}} P_i). \tag{4}$$

Definition 7: A *goal-driven behavior* B_g, which is denoted by $\hookrightarrow_g$, is an autonomic process in which the ith behavior in terms of process P_i is generated by the system itself, rather than being given, corresponding to the goal $@g_i\mathbf{ST}$, i.e.,

$$B_g \stackrel{\triangle}{=} \overset{n}{\underset{i=1}{\mathrm{R}}}(@g_i\mathbf{ST}\hookrightarrow_g P_i). \tag{5}$$

In Definition 7, the goal $@g_i\mathbf{ST}$ is in the system type $\mathbf{ST}$ that denotes a structure as follows.

Definition 8: A *goal*, which is denoted by $g\mathbf{ST}$, is a triple, i.e.,

$$g\mathbf{ST} = (P, \Omega, \Theta) \tag{6}$$

where P is a nonempty finite set of purposes or motivations, Ω is a set of constraints for the goal, and Θ is the environment of the goal.

Definition 9: A *decision-driven behavior* B_d, which is denoted by $\hookrightarrow_d$, is an autonomic process in which the ith behavior in terms of process P_i is generated by a given decision $@d_i\mathbf{ST}$, i.e.,

$$B_d \stackrel{\triangle}{=} \overset{n}{\underset{i=1}{\mathrm{R}}}(@d_i\mathbf{ST}\hookrightarrow_d P_i). \tag{7}$$

In Definition 9, the decision can be formally described as follows.

Definition 10: A *decision*, which is denoted by $d\mathbf{ST}$, is a selected alternative $a \in \mathcal{A}$ from a nonempty set of alternatives $\mathcal{A}$, based on a given set of criteria C, i.e.,

$$\begin{aligned} d &= f(\mathcal{A}, C) \\ &= f : \mathcal{A} \times C \to \mathcal{A}, \qquad \mathcal{A} \neq \varnothing. \end{aligned} \tag{8}$$

Definition 11: A *perception-driven behavior* B_p, which is denoted by $\hookrightarrow_p$, is a cognitive process in which the ith behavior in terms of process P_i is generated by the result of a perceptive process $@p_i\mathbf{PC}$, i.e.,

$$B_p \stackrel{\triangle}{=} \overset{n}{\underset{i=1}{\mathrm{R}}}(@p_i\mathbf{PC}\hookrightarrow_p P_i) \tag{9}$$

where $\mathbf{PC}$ stands for the type of process.

In Definition 11, the *perception result* $p\mathbf{PC}$ is an outcome of the cognitive process of perception that transforms sensory data in the sensory buffer memory (SBM) into interpreted information in the short-term memory (STM) of the brain in the same form as that of a goal.

Definition 12: An *inference-driven behavior* B_{inf}, which is denoted by $\hookrightarrow_{\mathrm{inf}}$, is a cognitive process in which the ith behavior in terms of process P_i is generated by the result of an inference process $@inf_i\mathbf{PC}$, i.e.,

$$B_{\mathrm{inf}} \stackrel{\triangle}{=} \overset{n}{\underset{i=1}{\mathrm{R}}}(@inf_i\mathbf{PC}\hookrightarrow_{\mathrm{inf}} P_i) \tag{10}$$

where formal inferences can be classified into the *deductive*, *inductive*, *abductive*, and *analogical* categories, as well as modal, probabilistic, and belief theories [46].

The *inference behavior* is the second extension of the cognitive CS on top of the imperative and autonomic CSs, which is a cognitive process that reasons about a possible causality from given premises based on known causal relations between a pair of cause and effect proven true by empirical arguments, theoretical inferences, or statistical regulations.

2) Hierarchy of Cybernetic Behavioral Spaces: The hierarchy of cybernetic behavioral spaces, as shown in Fig. 2, can be divided into the imperative, autonomic, and cognitive spaces of cybernetic behaviors. Conventional computing machines only cover the imperative CS. Computational intelligence [22] and adaptive systems extend the CS from the imperative to the autonomic ones. However, it covers little in the cognitive CS. CI and cognitive computers [46] encompass the entire domain of cybernetics and CSs, mainly the higher-level cognitive behaviors, such as those of perception and inference in both intelligent cybernetic systems and the brain.

Definition 13: The *imperative behavioral space* of cybernetics B_I is a set of instruction-triggered behaviors such as the event-driven behaviors (B_e), time-driven behaviors (B_t), and interrupt-driven behaviors (B_{int}), i.e.,

$$B_I \stackrel{\triangle}{=} \{B_e, B_t, B_{\mathrm{int}}\}. \tag{11}$$

An imperative system implemented on B_I may do nothing unless a specific program is loaded, in which the stored program transfers a general-purpose computer to a specific intelligent application. The imperative system is a traditional and passive system that implements deterministic, context-free, and stored-program-controlled behaviors.

Definition 14: The *autonomic behavioral space* of cybernetics B_A is a set of internally motivated and autonomously generated behaviors such as the goal-driven behaviors (B_g) and decision-driven behaviors (B_d) on the basis of the imperative space B_I, i.e.,

$$\begin{aligned} B_A &\stackrel{\triangle}{=} \{B_g, B_d\} \cup B_I \\ &= \{B_e, B_t, B_{\mathrm{int}}, B_g, B_d\}. \end{aligned} \tag{12}$$

An autonomic system implemented on B_A extends the passive and imperative cybernetic system on B_I to nondeterministic, context-dependent, and adaptive behaviors, such as the goal- and decision-driven behaviors [16], [23]. The autonomic systems do not rely on instructive and procedural information

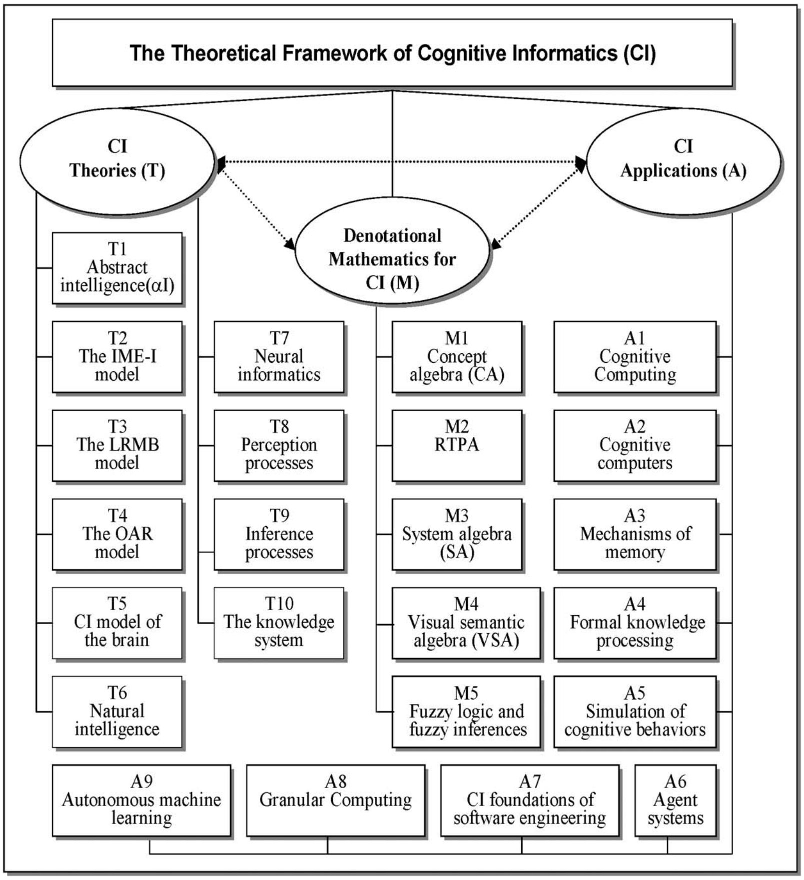


Fig. 3. Theoretical framework of CI.

but are dependent on internal status and willingness that are formed by long-term historical events and current rational or emotional goals.

Definition 15: The *cognitive behavioral space* of cybernetics B_C is a set of autonomously generated behaviors by internal cognitive processes such as the perception-driven behaviors (B_p) and inference-driven behaviors (B_{inf}) on the basis of the imperative space B_I and the autonomic space B_A, i.e.,

$$\begin{aligned} B_C &\triangleq \{B_p, B_{\text{inf}}\} \cup B_I \cup B_A \\ &= \{B_e, B_t, B_{\text{int}}, B_g, B_d, B_p, B_{\text{inf}}\}. \end{aligned} \tag{13}$$

As shown in Definition 15 and Fig. 2, a cognitive system implemented on B_C extends the conventional behaviors B_I and B_A to more powerful and intelligent behaviors, which are generated by internal and autonomous processes such as the perception and inference processes. With the possession of all the seven forms of intelligent behaviors in cybernetic space B_C, the cognitive system may advance closer to the intelligent power of human brains.

III. CI FACET OF CYBERNETICS

The entire architecture and domain of contemporary cybernetics, as shown in Fig. 1, may be described from the facets of CI and computational intelligence. This section elaborates the former; the latter will be presented in Section IV.

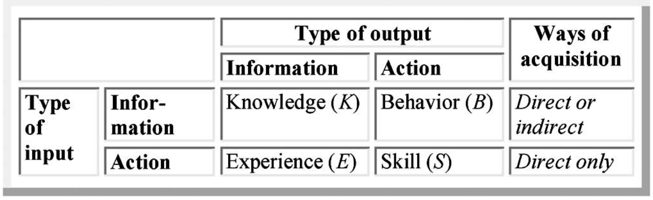
Definition 16: CI is a transdisciplinary inquiry of cybernetics, cognitive science, computer science, and information sciences that investigates into the internal information processing mechanisms and processes of the brain and NI, and their engineering applications via an interdisciplinary approach.

A. Theoretical Framework of CI

The structure of the theoretical framework of CI [44] is shown in Fig. 3, which covers ten fundamental theories such as *abstract intelligence* [51], the *information–matter–energy–intelligence* (IME-I) model, the LRMB, the *object–attribute-relation* (OAR) model of internal information representation in the brain, the CI model (CIM) of the brain, the mechanism of NI, neural informatics, the mechanism of human perception processes, the cognitive processes of formal inferences, and the formal knowledge system.

Four forms of denotational mathematics [46]–[50], such as *concept algebra*, *real-time process algebra* (RTPA), *system algebra*, and *visual semantic algebra* are created in CI, which enable a rigorous treatment of knowledge and behavior representations and manipulations in a formal and coherent framework. The new structures of denotational mathematics have extended the abstract objects that are under study in mathematics to a higher level, encompassing abstract concepts, behavioral processes, abstract systems, and visual semantic patterns beyond conventional mathematical entities such as numbers, sets, relations, functions, lattices, and groups.

TABLE I
MODEL OF COGNITIVE INFORMATION



		Type of output		**Ways of acquisition**
		Information	**Action**	
Type of input	**Information**	Knowledge (K)	Behavior (B)	*Direct or indirect*
	Action	Experience (E)	Skill (S)	*Direct only*

A wide range of applications of the descriptive mathematics in the context of CI have been identified, as shown in Fig. 3, particularly the cognitive computing methodologies and cognitive computer systems [24], [44], [45], mechanisms of human memory, simulation of the cognitive behaviors of the brain, autonomous agent systems, CI foundations of software engineering, granular computing [28], [34], [35], [37], [53], [61]–[63], and autonomous machine learning. The latest advances in CI have led to the development of cognitive computers, which extends computing techniques from imperative to cognitive computing that implements higher-level computing behaviors in the cognitive CS, as given in Definition 15.

The LRMB model [52] that provides a reference model for the design and implementation of cognitive systems is developed. LRMB presents a systematical view toward the formal description and modeling of architectures and behaviors of cognitive systems. The LRMB model explains the functional mechanisms and cognitive processes of the NI with 43 cognitive processes at seven layers known as the *sensation*, *memory*, *perception*, *action*, *metacognition*, *metainference*, and *higher cognitive layers* from the bottom up. Cognitive processes of the brain, particularly the perceptive and inference cognitive processes, are the fundamental models for describing cognitive system paradigms, such as robots, software-agent systems, and distributed intelligent networks.

B. Taxonomy of Cognitive Information in the Brain

Almost all modern disciplines of science and engineering deal with information and knowledge. However, data, information, and knowledge are conventionally considered as different entities in the literature [7], [60]. Based on the investigations in CI, particularly the research on the OAR model [44] and the mechanisms of internal information representation, the empirical classification of data, information, and knowledge may be revised. A CI theory on the relationship among data (sensational inputs), actions (behavioral outputs), and their internal representations such as knowledge, experience, and skill is that they are generally different forms of information. These forms of cognitive information may be classified based on how the internal information relates to the inputs and outputs (I/O) of the brain, as shown in Table I, which is known as the CIM.

According to the CIM, the taxonomy of cognitive information is determined by types of I/O of information to and from the brain, where both I/O can either be information or action. For a given cognitive process, if both I/O are abstract information, the internal information acquired is *knowledge*, if both I/O are empirical actions, the type of internal information is *skill*, and the remainder combinations between action/information and information/action produce *experience* and *behaviors*, respectively. In Table I, behavior is a new type of cognitive information modeled inside the brain, which embodies an abstract input to an observable behavioral output.

Definition 17: The *generic forms of cognitive information* state that there are four categories of internal information $\mathcal{I}$ in the brain known as *knowledge* (K), *behaviors* (B), *experience* (E), and *skills* (S), i.e.,

$$\mathcal{I} \triangleq (K, B, E, S). \tag{14}$$

It is noteworthy that the approaches to acquire knowledge/behavior and experience/skills are fundamentally different. Although knowledge or behaviors may directly and indirectly be acquired, skills and experiences can only be obtained directly by hands-on activities. Furthermore, the associated memories of the abstract information are different, where knowledge and experience are retained as abstract relations in long-term memory (LTM), while behaviors and skills are retained as wired neural connections in action buffer memory (ABM) [44].

C. Behavioral Model of Cybernetic Systems

The basic architecture of a generic cybernetic system can be refined by the behavioral models developed in Section II, which evolves cybernetic technologies from the imperative and autonomic behaviors to the cognitive behaviors, as shown in Fig. 2.

Definition 18: The *entire behavior space of cybernetics* B_{CC} is a layered hierarchical structure that encompasses the imperative B_I, autonomic B_A, and cognitive B_C spaces from the bottom up, i.e.,

$$\begin{aligned} B_{CC} &\triangleq (B_I, B_A, B_C) \\ &= \{ \quad (B_e, B_t, B_{\text{int}}) \qquad\qquad\qquad //B_I \\ &\qquad \|(B_e, B_t, B_{\text{int}}, B_g, B_d) \qquad\quad //B_A \\ &\qquad \|(B_e, B_t, B_{\text{int}}, B_g, B_d, B_p, B_{\text{inf}}) //B_C \, \}. \end{aligned} \tag{15}$$

On the basis of Definition 18, a generic cybernetic system on the cognitive cybernetic space may be rigorously modeled as shown in Fig. 4. The *behavioral model* of a generic cybernetic system $\S_{\text{CS}}$ is an abstract logical model denoted by a set of parallel cognitive computing architectures and behaviors, where $\|$ denotes the parallel relation between given components of the system. The cybernetic system is logically abstracted as a set of process behaviors and underlying architectures and resources, such as memory, ports, system clock, system variables, and states. A cybernetic system's behavior in terms of a set of processes P_i is controlled and dispatched by the system $\S_{\text{CS}}$, which is triggered by various external or system events and needs, such as interrupts, goals, decisions, perceptions, and inferences.

Corollary 1: The three layers of the behavioral spaces B_I, B_A, and B_C obey the following relations:

$$B_I \subseteq B_A \subseteq B_C. \tag{16}$$

$$
\begin{array}{ll}
\S_{\mathrm{CS}} \triangleq \text{Cybernetic\_System}\mathbf{ST} :: & \\
\quad \{ \ \text{// System Architectures} & \\
\qquad < \mathop{R}\limits_{i\mathbf{N}=0}^{n_{proc}\mathbf{N}-1} P_i\mathbf{ST}> & \text{// Processes} \\
\qquad || < \mathop{R}\limits_{addr\mathbf{P}=0}^{n_{MEM}\mathbf{H}-1} \text{MEM}[\text{ptr}\mathbf{P}]\mathbf{RT}> & \text{// Memory} \\
\qquad || < \mathop{R}\limits_{ptr\mathbf{P}=0}^{n_{PORT}\mathbf{H}-1} \text{PORT}[\text{ptr}\mathbf{P}]\mathbf{RT}> & \text{// Ports} \\
\qquad || <\S\text{t}\mathbf{TM}> & \text{// The system clock} \\
\qquad || < \mathop{R}\limits_{i\mathbf{N}=0}^{n_V\mathbf{N}-1} \text{V}_\text{i}\mathbf{RT}> & \text{// System variables} \\
\qquad || < \mathop{R}\limits_{i\mathbf{N}=0}^{n_S\mathbf{N}-1} \&\,\text{S}_\text{i}\mathbf{BL}> & \text{// System statuses} \\
\quad \} & \\
\ || \ \{ \ \text{// System Behaviors} & \\
\qquad || < \mathop{R}\limits_{k\mathbf{N}=0}^{n_e\mathbf{N}-1} @\text{e}_\text{k}\mathbf{S} \hookrightarrow \text{P}_\text{k}> & \text{// } \textit{Event}\text{-driven behaviors } (B_e) \\
\qquad || < \mathop{R}\limits_{k\mathbf{N}=0}^{n_t\mathbf{N}-1} @\text{t}_\text{k}\mathbf{TM} \hookrightarrow \text{P}_\text{k}> & \text{// } \textit{Time}\text{-driven behaviors } (B_t) \\
\qquad || < \mathop{R}\limits_{k\mathbf{N}=0}^{n_{\text{int}}\mathbf{N}-1} @\text{int}_\text{k}\odot \hookrightarrow \text{P}_\text{k} > & \text{// } \textit{Interrupt}\text{-driven behaviors } (B_{int}) \\
\qquad || < \mathop{R}\limits_{k\mathbf{N}=0}^{n_t\mathbf{N}-1} @\text{g}_\text{k}\mathbf{ST} \hookrightarrow \text{P}_\text{k}> & \text{// } \textit{Goal}\text{-driven behaviors } (B_g) \\
\qquad || < \mathop{R}\limits_{k\mathbf{N}=0}^{n_t\mathbf{N}-1} @\text{d}_\text{k}\mathbf{ST} \hookrightarrow \text{P}_\text{k}> & \text{// } \textit{Decision}\text{-driven behaviors } (B_d) \\
\qquad || < \mathop{R}\limits_{k\mathbf{N}=0}^{n_t\mathbf{N}-1} @\text{p}_\text{k}\mathbf{ST} \hookrightarrow \text{P}_\text{k}> & \text{// } \textit{Perception}\text{-driven behaviors } (B_p) \\
\qquad || < \mathop{R}\limits_{k\mathbf{N}=0}^{n_{\text{int}}\mathbf{N}-1} @\text{inf}_\text{k}\mathbf{ST} \hookrightarrow \text{P}_\text{k} > & \text{// } \textit{Inference}\text{-driven behaviors } (B_{inf}) \\
\quad \} &
\end{array}
$$

Fig. 4. Behavioral model of cybernetic systems.

Both Definition 18 and Corollary 1 indicate that any lower-layer CS is a subset of those of its higher layers. In other words, any higher-layer CS is a natural extension of those of lower layers, as shown in Fig. 2.

D. Roles of Information in the Evolution of NI

The profound uniqueness of cybernetics, CI, knowledge science, and intelligence science lies on the fact that its objects under study are located in a dual world as described in the following [25], [44], [46].

Definition 19: The *general worldview* of cybernetics, as shown in Fig. 5, reveals that the *natural world* (NW) is a dual encompassing both the *physical* (concrete) *world* (PW) and the *cyber* (abstract) *world* (CW).

In Fig. 5, there are four essences in modeling the NW, i.e., *matter* (M) and *energy* (E) for the PW, as well as *information* (I) and *intelligence* ($\mathfrak{I}$) for the abstract CW. In the IME-I model, the double arrows denote bidirectional relations between the essences in the CS, where known relations are denoted by solid lines, and relations yet to be discovered are denoted by dotted lines.

Definition 20: The IME-I model states that the NW, which forms the context of human and machine intelligence in cybernetics, is a dual. One aspect of it is the PW, and the other is the CW, where *intelligence* ($\mathfrak{I}$) plays a central role in the transformation between $I-M-E$.

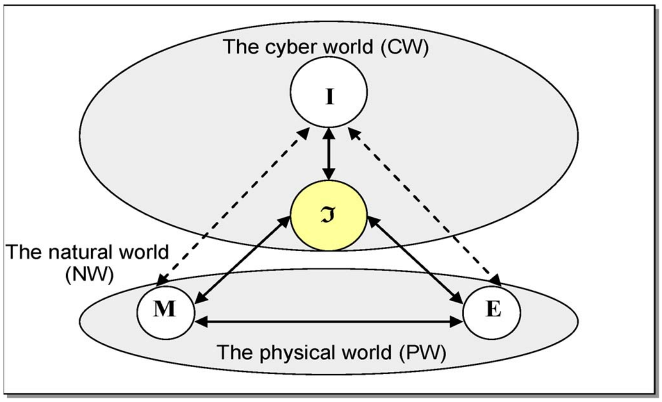


Fig. 5. IME-I model of cybernetics.

According to the IME-I model, information is the generic model for representing the abstract CW or the internal world of human beings. It is recognized that the basic evolutional need of mankind is to preserve both the species' biological traits and the cumulated information/knowledge bases. For the former, gene pools are adopted to pass human trait information via deoxyribonucleic acid (DNA) from generation to generation. However, for the latter, because acquired knowledge cannot be physiologically inherited between generations and individuals, various information means and systems are adopted to pass cumulated human information and knowledge.

It is noteworthy that intelligence ($\mathfrak{I}$) plays an irreplaceable role in the transformation between information, matter, and energy according to the IME-I model. It is observed that almost all cells in human bodies have a certain lifecycle in which they reproduce themselves via divisions. This mechanism allows human trait information to be transferred to the offspring through gene (DNA) replications during cell reproduction. However, it is observed that the most special mechanism of neurons in the brain is that they are the only type of cells in the human body that do not go through reproduction but remain alive throughout the entire human life [9], [32]. The advantage of this mechanism is that it enables the physiological representation and retention of acquired information and knowledge to be memorized in LTM. However, the key disadvantage of this mechanism is that it does not allow acquired information to be physiologically passed on to the next generation, because there is no DNA replication among memory neurons.

This physiological mechanism of neurons in the brain explains not only the foundation of memory and memorization but also the wonder why acquired information and knowledge cannot be passed and inherited physiologically from generation to generation. Therefore, to a certain extent, mankind relies very much on information on evolution than that of genes, because the basic characteristic of the human brain is intelligent information processing. In other words, the intelligent ability to cumulate and transfer information from generation to generation plays the vital role in mankind's evolution for both individuals and the entire species. This distinguishes human

TABLE II
APPROACHES TO IMPLEMENT NI AND AI

No.	Means	Approach	Category
1	Biological organisms	Naturally grown	NI
2	Silicon automata	Wired	AI
3	Computing systems	Programmed	AI
4	Other (in future)	Hybrid	NI + AI

beings from other species in natural evolution, where the latter cannot systematically pass acquired information by external and persistent information systems from generation to generation to enable it to grow cumulatively and exponentially.

IV. COMPUTATIONAL INTELLIGENCE FACET OF CYBERNETICS

Definition 21: Computational intelligence is a branch of cybernetics and AI that models human intelligence by computational methodologies and cognitively inspired models.

Intelligence is an important concept in cybernetics, CI, computing, and brain science [2], [4], [44], [51]. However, as reviewed in Section I, it was diversely perceived from different angles. A cybernetic perspective on natural and machine intelligence is focused on the transformation between *information, knowledge,* and *behavior*, where the nature of intelligence is the capability *to know* and *to do* what is possessed by both human brains and machine systems. In this view, a major objective of cybernetics is to answer the following.

1) How are the three forms of cognitive entities, i.e., information, knowledge, and behavior, transformed in the brain or a system?
2) What is the driving force to enable the transmissions?

A. GIM for Cybernetics

The abstract intelligence in general, and NI and AI in particular, can be classified into four categories, according to the variability between I/O to/from an intelligent system, known as the *routine, algorithmic, adaptive*, and *autonomic* intelligence from the bottom up. It is recognized that the basic approaches to implement intelligence can be classified as shown in Table II [46].

Definition 22: Intelligence, in the *narrow sense*, is a human or system ability that transforms information into behaviors, and in the *broad sense*, it is any human or system ability that autonomously transfers the forms of abstract information between *data*, *information*, *knowledge*, and *behaviors* in the brain.

According to Definition 22, NI is a set of intelligent behaviors possessed or implemented by human brains and those of other well-developed species. AI is intelligent behaviors possessed or implemented by machines or man-made systems.

The mechanisms of the NI can be described by a GIM as shown in Fig. 6. In the GIM 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). In the GIM model, any abstract object is physiologically retained in a particular type of memory, such as the SBM, STM, LTM, and ABM. These are the neural informatics foundation of NI and the physiological evidences of why NI can be classified into four forms as given in the following.

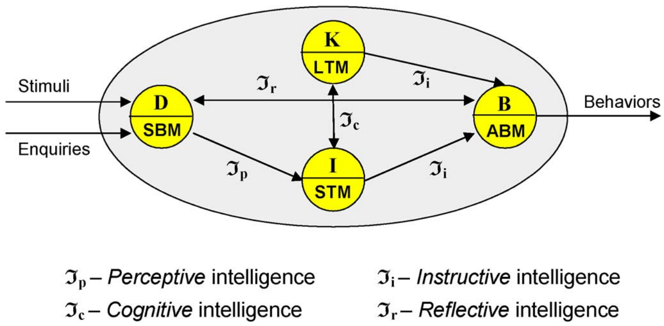


Fig. 6. GIM.

Definition 23: The *nature of intelligence* states that *intelligence* $\Im$ can be classified into four forms called *perceptive intelligence* $\Im_p$, *cognitive intelligence* $\Im_c$, *instructive intelligence* $\Im_i$, and *reflective intelligence* $\Im_r$, as modeled by

$$\begin{aligned} \Im \stackrel{\triangle}{=} \Im_p &: D \to I \text{ (Perceptive)} \\ \|\Im_c &: I \to K \text{ (Cognitive)} \\ \|\Im_i &: I \to B \text{ (Instructive)} \\ \|\Im_r &: D \to B \text{ (Reflective).} \end{aligned} \tag{17}$$

The four abstract objects can be rigorously described as follows.

Definition 24: The abstract object data D in GIM is a quantitative representation of external entities by a function r_d that maps an external message or signal M into a specific measurement scale S_k, i.e.,

$$\begin{aligned} D &\stackrel{\triangle}{=} r_d : M \to S_k \\ &= \log_k M, \qquad k_{\min} = 2 \end{aligned} \tag{18}$$

where k is the base of the measurement scale, and the minimum of k, which is $k_{\min}$, is 2.

Definition 25: The abstract object *information* I in GIM is a perceptive interpretation of data by a function r_i that maps the data into a concept C, i.e.,

$$I \stackrel{\triangle}{=} r_i : D \to C, \qquad r_i \in \Re \tag{19}$$

where $\Re$ is the set of relational operations of concept algebra with C as a *concept* in the form given as follows [46].

Definition 26: An *abstract concept* c on U, $c \sqsubseteq U$, is a 5-tuple, i.e.,

$$c \stackrel{\triangle}{=} (O, A, R^c, R^i, R^o) \tag{20}$$

where

$\sqsubseteq$	denotes that a set or structure (tuple) is a substructure or derivation of another known structure;

O	nonempty set of objects of the concept $O = \{o_1, o_2, \ldots, o_m\} \subseteq \text{Þ}\, U$, where $\text{Þ}\, U$ denotes a power set of the universal set U;
A	nonempty set of attributes $A = \{a_1, a_2, \ldots, a_n\} \subseteq \text{Þ}\, M$, where M is the universal set of attributes of U;
$R^c \subseteq O \times A$	set of internal relations;
$R^i \subseteq A' \times A$	set of input relations, where $A' \sqsubseteq C' \wedge A \sqsubseteq c$, and C' is a set of external concepts $C' \subseteq \Theta_C$. For convenience, $R^i = A' \times A$ may simply be denoted as $R^i = C' \times c$;
$R^o \subseteq c \times C'$	set of output relations.

Definition 27: The abstract object *knowledge* K in GIM is a perceptive representation of information by a function r_k that maps a given concept C_0 into all related concepts, i.e.,

$$K \triangleq r_k : C_0 \to \left(\mathop{\mathrm{X}}_{i=1}^{n} C_i \right), \qquad r_k \in \Re \tag{21}$$

where $\Re = \{\Rightarrow, \overset{+}{\Rightarrow}, \overset{-}{\Rightarrow}, \overset{\sim}{\Rightarrow}, \uplus, \pitchfork, \Lleftarrow, \vdash, \to\}$ [46].

Definition 28: The *entire knowledge* $\mathfrak{K}$ is represented by a *concept network*, which is a hierarchical network of concepts interlinked by the set of nine compositional operations $\Re$ defined in concept algebra, i.e.,

$$\mathfrak{K} = \Re : \mathop{\mathrm{X}}_{i=1}^{n} C_i \to \mathop{\mathrm{X}}_{j=1}^{n} C_j. \tag{22}$$

Definition 29: The abstract object *behavior* B in GIM is an embodied motivation M by a function r_b that maps a motivation M into an executable process P, i.e.,

$$\begin{aligned} B &\triangleq r_b : M \to P \\ &= \mathop{\mathrm{R}}_{k=1}^{m} (@e_k \hookrightarrow P_k) \\ &= \mathop{\mathrm{R}}_{k=1}^{m} \left[@e_k \hookrightarrow \mathop{\mathrm{R}}_{i=1}^{n-1} (p_i(k) r_{ij}(k) p_j(k)) \right], \\ &\qquad\qquad j = i + 1;\ r_{ij} \in \Re_{\mathrm{RTPA}} \end{aligned} \tag{23}$$

where M is generated by external stimuli or events and/or internal emotions or willingness, which are collectively represented by a set of events $E = \{e_1, e_2, \ldots, e_m\}$.

In Definition 29, P_k is represented by a set of cumulative relational subprocesses $p_i(k)$. The mathematical model of the cumulative relational processes may be referred to [46].

According to Definitions 22 and 23 in the context of the GIM model, the narrow sense of intelligence in cybernetics corresponds to the instructive and reflective intelligence, while the broad sense of intelligence in cybernetics includes all four forms of intelligence, i.e., the perceptive, cognitive, instructive, and reflective intelligence.

B. Compatibility of Natural and Machine Intelligence

Cybernetics and CI reveals the equivalence and compatibility between NI and AI. It is rational to perceive that NI should be well understood before AI may be studied on a rigorous basis. It also indicates that any machine that may implement a part of human behaviors and actions in information processing may be treated as possessing some extent of intelligence.

According to the GIM model, natural and machine (artificial) intelligence share the same CI foundation as described in the following, because the latter is a machine implementation of the former.

Corollary 2: The *compatible intelligent capability* states that NI and AI are compatible by sharing the same mechanisms of intelligent capability and behaviors, i.e.,

$$\mathrm{AI} \cong \mathrm{NI}. \tag{24}$$

At the logical level, the NI of the brain shares the same mechanisms as those of AI. The differences between NI and AI are only distinguishable by 1) the means of implementation and 2) the level of intelligent capability.

Corollary 3: The *inclusive intelligent capability* states that AI is a subset of NI, i.e.,

$$\mathrm{AI} \subseteq \mathrm{NI}. \tag{25}$$

Corollary 3 indicates that AI is dominated by NI. Therefore, one should not expect a computer or a software system to solve a problem where humans cannot. In other words, no AI or computer systems may be designed and/or implemented for a given problem where there is no solution collectively being known by human beings. Furthermore, Corollaries 2 and 3 explain that the development and implementation of AI rely on the understanding of the mechanisms and laws of NI in cybernetics.

On the basis of Corollary 2, it is recognized that the human brain, at the basic level, has no difference from those of other advanced animal species. However, the brain possesses unique advantages as identified in CI known as the quantitative and qualitative advantages. The former states that the magnitude of the memory capacity of the brain is tremendously greater than that of the closest species. The latter states that the possession of the abstract layer of memory and the abstract reasoning capacity makes the human brain fundamentally powerful in reasoning on the basis of the quantitative advantage.

Corollary 4: The *principal intelligent advantages* state that, on the basis of the two principal advantages with the *qualitative* and *quantitative* properties, humans gain the power as the most intelligent species in the world.

On the basis of Corollaries 1–4, the studies on NI and AI may be unified into a common framework in cybernetics and CI, where the fundamental models of GIM, LRMB [52], and OAR [44] play important roles in exploring the natural and machine intelligence.

It is noteworthy that the perception and inference of NI is carried out at the level of concepts, while that of machine intelligence is at the level of data and attribute information, which is lower than concept. Therefore, the new mathematical structure of concept algebra [47], [50] will provide a foundation for denoting and manipulating knowledge and formal inferences in the future-generation intelligent computers known as *cognitive computers* based on the improved understanding of the mechanisms of NI in cybernetics and CI.

V. CONCLUSION

This paper has explored the architecture, theoretical foundations, and engineering paradigms of contemporary cybernetics. Two cutting-edge facets of cybernetics known as CI and computational intelligence have been introduced in the cybernetic context. The GIM that provides a foundation to explain the mechanisms of the *perceptive*, *cognitive*, *instructive*, and *reflective intelligence* in cybernetics has been formally developed. It has been recognized that *abstract intelligence*, in the *narrow sense*, is a human or system ability that transfers information into behaviors, and in the *broad sense*, it is any human or system ability that autonomously transfers the forms of abstract information between *data*, *information*, *knowledge*, and *behaviors* in the brain. Based on the cybernetic models, a systematical reduction from the logical, functional, physiological, and biological levels has been delineated to form a coherent theory for the studies on natural and machine intelligence in cybernetics.

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Contemporary Cybernetics and Its Facets of Cognitive Informatics and Computational Intelligence

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***Abstract*—This paper explores the architecture, theoretical foundations, and paradigms of contemporary cybernetics from perspectives of cognitive informatics (CI) and computational intelligence. The modern domain and the hierarchical behavioral model of cybernetics are elaborated at the imperative, autonomic, and cognitive layers. The CI facet of cybernetics is presented, which explains how the brain may be mimicked in cybernetics via CI and neural informatics. The computational intelligence facet is described with a generic intelligence model of cybernetics. The compatibility between natural and cybernetic intelligence is analyzed. A coherent framework of contemporary cybernetics is presented toward the development of transdisciplinary theories and applications in cybernetics, CI, and computational intelligence.**

***Index Terms*—Autonomic systems, behavioral models, cognitive informatics, cognitive models, cognitive systems, computational intelligence, cybernetics, imperative systems, machine intelligence, mathematical models, natural intelligence.**

I. INTRODUCTION

CYBERNETICS is the science of communication and autonomous control in both machines and living things as proposed by Norbert Wiener in 1948. In his work on *Cybernetics or Control and Communication in the Animal and the Machine* [57], Wiener initiated the field of cybernetics to provide a mathematical means for studying adaptive and autonomous systems. Cybernetics mimics information communicated in machines with that of the brain and nervous systems. It also attempts to elaborate human behavior by cybernetic engineering concepts [3], [4], [13], [21], [29], [51], [58]. Cybernetics constitutes one of the roots of modern cognitive science.

The history of cybernetics can be traced back to the works of Wiener, von Neumann, Turing, and Shannon as early as in the 1940s [36], [39], [41]–[43], [57], [58]. In the same period, McCarthy *et al.* proposed the term *artificial intelligence* (AI) [30], [32]. Kleene analyzed the relations of automata and nerve nets [26], and Widrow and Lehr initiated the technology of *artificial neural networks* in the 1950s [59] based on multilevel, distributed, dynamic, interactive, and self-organizing nonlinear networks [1], [8], [12]. The concepts of robotics [6] and expert systems [11] were developed in the 1970s and 1980s, respectively. Then, intelligent systems [33] and software agents [14], [17] emerged in the 1990s. These events and developments lead to the development of contemporary cybernetics.

It was conventionally deemed that only human beings and other advanced species possess intelligence. However, the development of computers, robots, and cybernetic systems indicates that intelligence may also be created or implemented by machines and man-made systems. Therefore, it is one of the key objectives in cybernetics to seek a coherent theory for explaining the mechanisms of both natural and machine (artificial) intelligence [4], [44], [57], [58].

The history of investigation into the brain and natural intelligence (NI) is as long as the history of mankind. Early studies on cybernetics and NI are represented by works of Vygotsky, Spearman, and Thurstone [60]. Lev Vygotsky (1896–1934) presented a communication view that perceives intelligence as an inter- and intrapersonal communication in a social context. Charles E. Spearman (1863–1945) and Lois L. Thurstone (1887–1955) proposed the *factor theory* [27], in which seven factors of intelligence are identified such as the *verbal comprehension*, *word fluency*, *number facility*, *spatial visualization*, *associative memory*, *perceptual speed*, and *reasoning*. Jensen's *two-level theory* [18]–[20] classified intelligence into the *associative* and *cognitive* ability levels. The former is the ability to process external stimuli and events, while the latter is the ability to carry out reasoning and problem solving. Gardner's *multiple intelligence theory* [10] identified eight forms of intelligence, which are those of *linguistic, logical–mathematical*, *musical*, *spatial*, *bodily kinesthetic*, *naturalist*, *interpersonal*, and *intrapersonal*. He perceived that intelligence is an ability to solve a problem or create a product within a specific cultural setting.

In the turn of the new century, Sternberg's *triarchic theory* [38] modeled intelligence in three dimensions known as the *analytic*, *practical*, and *creative* intelligence. He perceived intelligence as the ability to adapt, shape, and select environments

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to accomplish one's goals and those of society. Lefton *et al.* [27] defined intelligence as the overall capacity of the individual to act purposefully, to think rationally, and to deal effectively with the social and cultural environment. They perceived that intelligence is not a thing, but a process that is affected by a person's experiences in the environment. Wang's *abstract intelligent theory* (αI) [44], [51] revealed that NI is the driving force that transforms cognitive information in the forms of data, knowledge, skill, and behavior. A *Layered Reference Model of the Brain* (LRMB) has been developed [52], which encompasses 43 cognitive processes at seven layers known as the *sensation*, *memory*, *perception*, *action*, *metacognitive*, *metainference*, and *higher cognitive layers* from the bottom up.

The development of classic and contemporary cybernetics, cognitive informatics (CI), and the cross fertilization between computer science, system science, computer/software engineering, neuropsychology, and computational intelligence have led to a wide range of interesting new research fields known as CI [44], [45], [47], [49], [51], [54], [55]. CI is an interdisciplinary research field that tackles the fundamental problems of modern cybernetics, information science, systems science, computer/software engineering, computational intelligence, cognitive science, neuropsychology, and life sciences. Almost all of the hard problems yet to be solved in the aforementioned areas share a common root in the understanding of the mechanisms of the NI and cognitive processes of the brain. Therefore, CI is perceived as a new frontier that explores the internal information processing mechanisms of the brain and their engineering applications in cybernetics, computing, and information technology industry.

This paper attempts to explore the theoretical foundations and engineering paradigms of contemporary cybernetics, particularly its newly developed facets known as CI and computational intelligence. In the remainder of this paper, the contemporary architecture of cybernetics and its hierarchical behavior model at the imperative, autonomic, and cognitive layers are elaborated in Section II. The CI facet of cybernetics is presented in Section III, which explains how the brain may be mimicked in cybernetics via CI. The computational intelligence facet of cybernetics is described in Section IV, which presents the generic intelligence model (GIM) of cybernetics and analyzes the compatibility between the natural and cybernetic intelligence. As a result, a coherent framework of contemporary cybernetics is elaborated toward the development of interdisciplinary and transdisciplinary theories and application paradigms in cybernetics, CI, and computational intelligence.

II. CONTEMPORARY ARCHITECTURE OF CYBERNETICS

Studies in cybernetics cover biologically, cognitively, and intelligently motivated computational paradigms [5], [15], [21], [31], [40], [51] such as abstract intelligence, neural networks, genetic algorithms, fuzzy systems, autonomic systems, cognitive systems, robotics, CI, and computational intelligence.

Definition 1: Cybernetics is the science of communication and control in humans, machines, organizations, and societies across the reductive hierarchy of neural, cognitive, functional, and logical levels.

A. Domain of Cybernetics

The domain and architecture of contemporary cybernetics encompass a wide range of coherent fields, as shown in Fig. 1, from the machine, natural, and organizational intelligence to social intelligence in the horizontal scopes and from the logical, functional, and cognitive models to neural (biological) models in the vertical reductive hierarchy. Therefore, cybernetics in nature is a multidisciplinary and transdisciplinary inquiry of cognitive information processing and autonomic systems.

As shown in Fig. 1, the double arrows indicate abstraction/reduction or aggregation/specification. The scope of contemporary cybernetics in the horizontal domains has been extended from mainly machine intelligence to natural, organizational, and societal intelligence. In the vertical dimension, the reduction levels of cybernetics have been extended from logical and functional models to cognitive and neural models.

With the notion of *functional reductionism*, a logical model of the NI is needed to explain formally the high-level mechanisms of the brain on the basis of observations at the biological and physiological levels. The logical model of the brain is the highest level of abstraction for explaining its cognitive mechanisms. Based on it, a systematical reduction from the logical, functional, physiological, and biological levels may be established in both the top–down and bottom–up approaches, which will enable the establishment of a coherent theory of NI and cybernetics.

It is noteworthy that, at the overall level, contemporary cybernetics has evolved from pure autonomic communication and control theories to CI [44], [45] and computational intelligence [22]. The former provides an extended NI and internal information-processing perspective to cybernetics, while the latter studies a computation modeling perspective to cybernetics.

B. Behavioral Spaces of Cybernetics

Behaviorism is a doctrine of psychology and CI that studies the association between a given stimulus and an observed response of human brains and cybernetic systems [45], [52]. CI reveals that human and machine behaviors may be classified into four categories known as the *perceptive*, *cognitive*, *instructive*, and *reflective* behaviors [46].

The behavioral space of cybernetics and cybernetic systems can be classified into the imperative, autonomic, and cognitive cyberspaces (CSs), as shown in Fig. 2. The *imperative CS* is an enclosure of instructive and passive behaviors. The *autonomic CS* is an enclosure of internally motivated behaviors beyond those of the imperative space. The *cognitive CS* is an enclosure of perceptive and inference-driven behaviors beyond those of both imperative and autonomic spaces. More formal descriptions of the three forms of CSs will be presented in Section II-B2, after each layer of the hierarchical CSs and their basic properties is formally modeled as follows.

1) Behavioral Models of Cybernetics: Before the elaboration of the behavioral spaces of cybernetics, the taxonomies of cybernetic behaviors at different layers of cybernetics, as shown in Fig. 2, are formally modeled in the following.

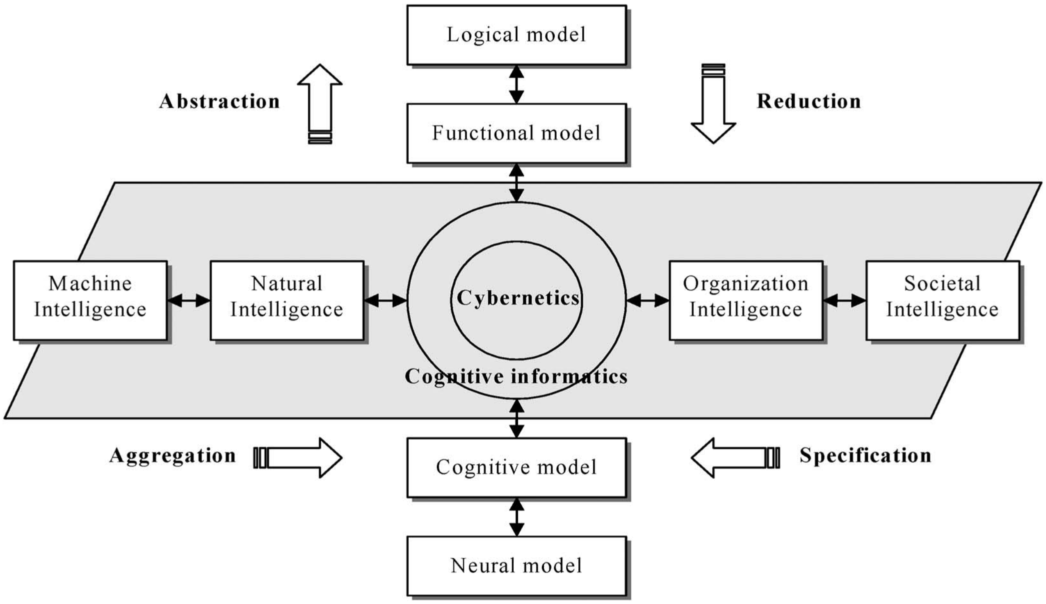


Fig. 1. Architecture of contemporary cybernetics and CI.

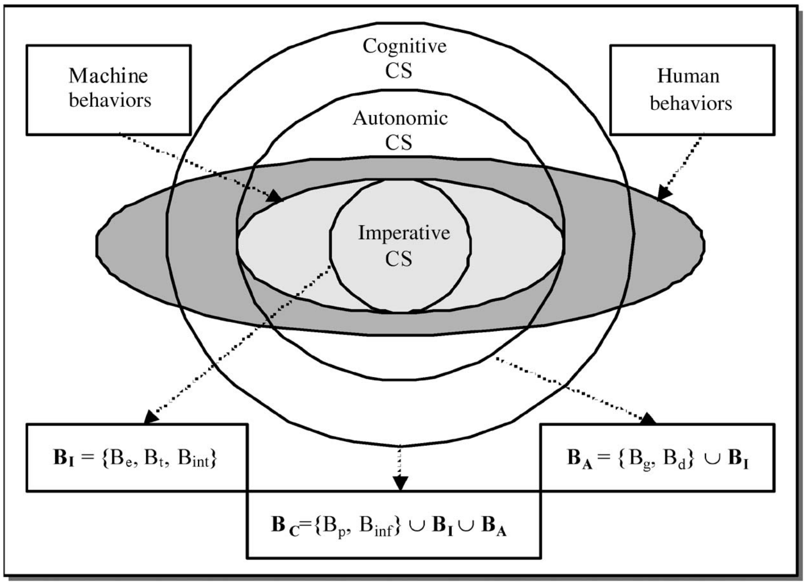


Fig. 2. Behavioral spaces of cybernetics.

Definition 2: An *event* is an abstract variable that represents an external stimulus to a system or the occurrence of an internal change of status, such as an action of users, an updating of the environment, and a change of the value of a control variable.

The types of events that may trigger a behavior can be classified into operational ($@e\mathbf{S}$), time ($@t\mathbf{TM}$), and interrupt ($@int{\odot}$) events, where @ is the *event prefix*, and $\mathbf{S}$, $\mathbf{TM}$, and $\odot$ are three of the type suffixes, respectively. The *interrupt event* is a kind of special event that models the interruption of an executing process, the temporal handover of controls to an interrupt service routine, and the return of control after its completion.

Definition 3: An *interrupt*, which is denoted by $\lightning$, is a parallel process relation in which a running process P is temporarily held by another higher-priority process Q via an interrupt event ($@int{\odot}$) at the interrupt point $\odot$, and the interrupted process will be resumed when the high-priority process has been completed, i.e.,

$$P \lightning Q \triangleq P \parallel (@int{\odot} \nearrow Q \searrow \odot) \tag{1}$$

where $\nearrow$ and $\searrow$ denote an *interrupt service* and an *interrupt return*, respectively.

In general, all types of events, including the operational, timing, and interrupt events, are captured by the system to dispatch a designated behavior.

Definition 4: An *event-driven behavior* B_e, which is denoted by $\hookrightarrow_e$, is an imperative process in which the ith behavior in terms of a designated process P_i is triggered by a predefined event $@e_i\mathbf{S}$, i.e.,

$$B_e \triangleq \overset{n}{\underset{i=1}{R}} (@e_i\mathbf{S} \hookrightarrow_e P_i) \tag{2}$$

where the big-R notation is a mathematical calculus that denotes a sequence of repetitive/iterative behaviors or a set of recurring structures [46].

Definition 5: A *time-driven behavior* B_t, which is denoted by $\hookrightarrow_t$, is an imperative process in which the ith behavior in terms of process P_i is triggered by a predefined point of time $@t_i\mathbf{TM}$, i.e.,

$$B_t \triangleq \mathop{\mathrm{R}}\limits_{i=1}^{n} (@t_i\mathbf{TM} \hookrightarrow_t P_i) \tag{3}$$

where $@t_i\mathbf{TM}$ may be a system timing or an external timing event.

Definition 6: An *interrupt-driven behavior* B_{int}, which is denoted by $\hookrightarrow_{\text{int}}$, is an imperative process in which the ith behavior in terms of process P_i is triggered by a predefined system interrupt $(@int\,\odot)$, i.e.,

$$B_{\text{int}} \triangleq \mathop{\mathrm{R}}\limits_{i=1}^{n} (@int_i \odot \hookrightarrow_{\text{int}} P_i). \tag{4}$$

Definition 7: A *goal-driven behavior* B_g, which is denoted by $\hookrightarrow_g$, is an autonomic process in which the ith behavior in terms of process P_i is generated by the system itself, rather than being given, corresponding to the goal $@g_i\mathbf{ST}$, i.e.,

$$B_g \triangleq \mathop{\mathrm{R}}\limits_{i=1}^{n} (@g_i\mathbf{ST} \hookrightarrow_g P_i). \tag{5}$$

In Definition 7, the goal $@g_i\mathbf{ST}$ is in the system type $\mathbf{ST}$ that denotes a structure as follows.

Definition 8: A *goal*, which is denoted by $g\mathbf{ST}$, is a triple, i.e.,

$$g\mathbf{ST} = (P, \Omega, \Theta) \tag{6}$$

where P is a nonempty finite set of purposes or motivations, Ω is a set of constraints for the goal, and Θ is the environment of the goal.

Definition 9: A *decision-driven behavior* B_d, which is denoted by $\hookrightarrow_d$, is an autonomic process in which the ith behavior in terms of process P_i is generated by a given decision $@d_i\mathbf{ST}$, i.e.,

$$B_d \triangleq \mathop{\mathrm{R}}\limits_{i=1}^{n} (@d_i\mathbf{ST} \hookrightarrow_d P_i). \tag{7}$$

In Definition 9, the decision can be formally described as follows.

Definition 10: A *decision*, which is denoted by $d\mathbf{ST}$, is a selected alternative $a \in \mathcal{A}$ from a nonempty set of alternatives $\mathcal{A}$, based on a given set of criteria C, i.e.,

$$\begin{aligned} d &= f(\mathcal{A}, C) \\ &= f : \mathcal{A} \times C \to \mathcal{A}, \qquad \mathcal{A} \neq \varnothing. \end{aligned} \tag{8}$$

Definition 11: A *perception-driven behavior* B_p, which is denoted by $\hookrightarrow_p$, is a cognitive process in which the ith behavior in terms of process P_i is generated by the result of a perceptive process $@p_i\mathbf{PC}$, i.e.,

$$B_p \triangleq \mathop{\mathrm{R}}\limits_{i=1}^{n} (@p_i\mathbf{PC} \hookrightarrow_p P_i) \tag{9}$$

where $\mathbf{PC}$ stands for the type of process.

In Definition 11, the *perception result* $p\mathbf{PC}$ is an outcome of the cognitive process of perception that transforms sensory data in the sensory buffer memory (SBM) into interpreted information in the short-term memory (STM) of the brain in the same form as that of a goal.

Definition 12: An *inference-driven behavior* B_{inf}, which is denoted by $\hookrightarrow_{\text{inf}}$, is a cognitive process in which the ith behavior in terms of process P_i is generated by the result of an inference process $@inf_i\mathbf{PC}$, i.e.,

$$B_{\text{inf}} \triangleq \mathop{\mathrm{R}}\limits_{i=1}^{n} (@inf_i\mathbf{PC} \hookrightarrow_{\text{inf}} P_i) \tag{10}$$

where formal inferences can be classified into the *deductive*, *inductive*, *abductive*, and *analogical* categories, as well as modal, probabilistic, and belief theories [46].

The *inference behavior* is the second extension of the cognitive CS on top of the imperative and autonomic CSs, which is a cognitive process that reasons about a possible causality from given premises based on known causal relations between a pair of cause and effect proven true by empirical arguments, theoretical inferences, or statistical regulations.

2) Hierarchy of Cybernetic Behavioral Spaces: The hierarchy of cybernetic behavioral spaces, as shown in Fig. 2, can be divided into the imperative, autonomic, and cognitive spaces of cybernetic behaviors. Conventional computing machines only cover the imperative CS. Computational intelligence [22] and adaptive systems extend the CS from the imperative to the autonomic ones. However, it covers little in the cognitive CS. CI and cognitive computers [46] encompass the entire domain of cybernetics and CSs, mainly the higher-level cognitive behaviors, such as those of perception and inference in both intelligent cybernetic systems and the brain.

Definition 13: The *imperative behavioral space* of cybernetics B_I is a set of instruction-triggered behaviors such as the event-driven behaviors (B_e), time-driven behaviors (B_t), and interrupt-driven behaviors (B_{int}), i.e.,

$$B_I \triangleq \{B_e, B_t, B_{\text{int}}\}. \tag{11}$$

An imperative system implemented on B_I may do nothing unless a specific program is loaded, in which the stored program transfers a general-purpose computer to a specific intelligent application. The imperative system is a traditional and passive system that implements deterministic, context-free, and stored-program-controlled behaviors.

Definition 14: The *autonomic behavioral space* of cybernetics B_A is a set of internally motivated and autonomously generated behaviors such as the goal-driven behaviors (B_g) and decision-driven behaviors (B_d) on the basis of the imperative space B_I, i.e.,

$$\begin{aligned} B_A &\triangleq \{B_g, B_d\} \cup B_I \\ &= \{B_e, B_t, B_{\text{int}}, B_g, B_d\}. \end{aligned} \tag{12}$$

An autonomic system implemented on B_A extends the passive and imperative cybernetic system on B_I to nondeterministic, context-dependent, and adaptive behaviors, such as the goal- and decision-driven behaviors [16], [23]. The autonomic systems do not rely on instructive and procedural information

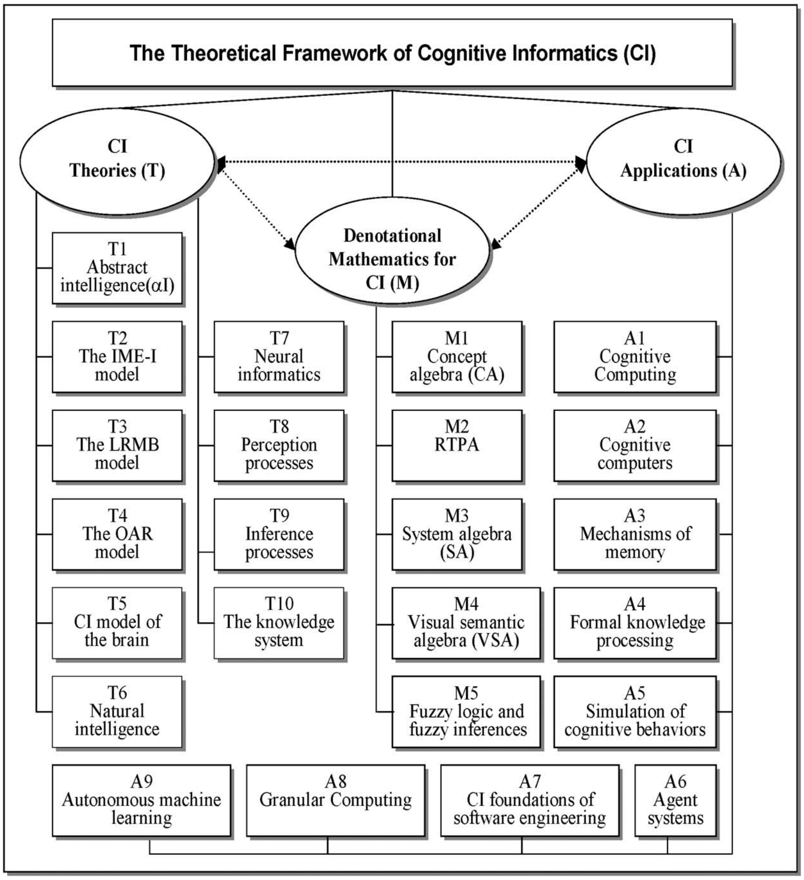


Fig. 3. Theoretical framework of CI.

but are dependent on internal status and willingness that are formed by long-term historical events and current rational or emotional goals.

Definition 15: The *cognitive behavioral space* of cybernetics B_C is a set of autonomously generated behaviors by internal cognitive processes such as the perception-driven behaviors (B_p) and inference-driven behaviors (B_{inf}) on the basis of the imperative space B_I and the autonomic space B_A, i.e.,

$$\begin{aligned} B_C &\triangleq \{B_p, B_{\text{inf}}\} \cup B_I \cup B_A \\ &= \{B_e, B_t, B_{\text{int}}, B_g, B_d, B_p, B_{\text{inf}}\}. \end{aligned} \qquad (13)$$

As shown in Definition 15 and Fig. 2, a cognitive system implemented on B_C extends the conventional behaviors B_I and B_A to more powerful and intelligent behaviors, which are generated by internal and autonomous processes such as the perception and inference processes. With the possession of all the seven forms of intelligent behaviors in cybernetic space B_C, the cognitive system may advance closer to the intelligent power of human brains.

III. CI FACET OF CYBERNETICS

The entire architecture and domain of contemporary cybernetics, as shown in Fig. 1, may be described from the facets of CI and computational intelligence. This section elaborates the former; the latter will be presented in Section IV.

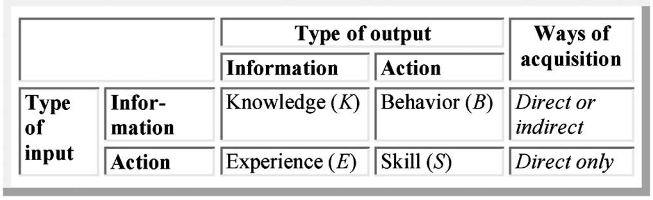
Definition 16: CI is a transdisciplinary inquiry of cybernetics, cognitive science, computer science, and information sciences that investigates into the internal information processing mechanisms and processes of the brain and NI, and their engineering applications via an interdisciplinary approach.

A. Theoretical Framework of CI

The structure of the theoretical framework of CI [44] is shown in Fig. 3, which covers ten fundamental theories such as *abstract intelligence* [51], the *information–matter–energy–intelligence* (IME-I) model, the LRMB, the *object–attribute-relation* (OAR) model of internal information representation in the brain, the CI model (CIM) of the brain, the mechanism of NI, neural informatics, the mechanism of human perception processes, the cognitive processes of formal inferences, and the formal knowledge system.

Four forms of denotational mathematics [46]–[50], such as *concept algebra*, *real-time process algebra* (RTPA), *system algebra*, and *visual semantic algebra* are created in CI, which enable a rigorous treatment of knowledge and behavior representations and manipulations in a formal and coherent framework. The new structures of denotational mathematics have extended the abstract objects that are under study in mathematics to a higher level, encompassing abstract concepts, behavioral processes, abstract systems, and visual semantic patterns beyond conventional mathematical entities such as numbers, sets, relations, functions, lattices, and groups.

TABLE I
MODEL OF COGNITIVE INFORMATION



		Type of output		**Ways of acquisition**
		Information	**Action**	
Type of input	**Information**	Knowledge (*K*)	Behavior (*B*)	*Direct or indirect*
	Action	Experience (*E*)	Skill (*S*)	*Direct only*

A wide range of applications of the descriptive mathematics in the context of CI have been identified, as shown in Fig. 3, particularly the cognitive computing methodologies and cognitive computer systems [24], [44], [45], mechanisms of human memory, simulation of the cognitive behaviors of the brain, autonomous agent systems, CI foundations of software engineering, granular computing [28], [34], [35], [37], [53], [61]–[63], and autonomous machine learning. The latest advances in CI have led to the development of cognitive computers, which extends computing techniques from imperative to cognitive computing that implements higher-level computing behaviors in the cognitive CS, as given in Definition 15.

The LRMB model [52] that provides a reference model for the design and implementation of cognitive systems is developed. LRMB presents a systematical view toward the formal description and modeling of architectures and behaviors of cognitive systems. The LRMB model explains the functional mechanisms and cognitive processes of the NI with 43 cognitive processes at seven layers known as the *sensation*, *memory*, *perception*, *action*, *metacognition*, *metainference*, and *higher cognitive layers* from the bottom up. Cognitive processes of the brain, particularly the perceptive and inference cognitive processes, are the fundamental models for describing cognitive system paradigms, such as robots, software-agent systems, and distributed intelligent networks.

B. Taxonomy of Cognitive Information in the Brain

Almost all modern disciplines of science and engineering deal with information and knowledge. However, data, information, and knowledge are conventionally considered as different entities in the literature [7], [60]. Based on the investigations in CI, particularly the research on the OAR model [44] and the mechanisms of internal information representation, the empirical classification of data, information, and knowledge may be revised. A CI theory on the relationship among data (sensational inputs), actions (behavioral outputs), and their internal representations such as knowledge, experience, and skill is that they are generally different forms of information. These forms of cognitive information may be classified based on how the internal information relates to the inputs and outputs (I/O) of the brain, as shown in Table I, which is known as the CIM.

According to the CIM, the taxonomy of cognitive information is determined by types of I/O of information to and from the brain, where both I/O can either be information or action. For a given cognitive process, if both I/O are abstract information, the internal information acquired is *knowledge*, if both I/O are empirical actions, the type of internal information is *skill*, and the remainder combinations between action/information and information/action produce *experience* and *behaviors*, respectively. In Table I, behavior is a new type of cognitive information modeled inside the brain, which embodies an abstract input to an observable behavioral output.

Definition 17: The *generic forms of cognitive information* state that there are four categories of internal information $\mathcal{I}$ in the brain known as *knowledge* (K), *behaviors* (B), *experience* (E), and *skills* (S), i.e.,

$$\mathcal{I} \overset{\wedge}{=} (K, B, E, S). \tag{14}$$

It is noteworthy that the approaches to acquire knowledge/behavior and experience/skills are fundamentally different. Although knowledge or behaviors may directly and indirectly be acquired, skills and experiences can only be obtained directly by hands-on activities. Furthermore, the associated memories of the abstract information are different, where knowledge and experience are retained as abstract relations in long-term memory (LTM), while behaviors and skills are retained as wired neural connections in action buffer memory (ABM) [44].

C. Behavioral Model of Cybernetic Systems

The basic architecture of a generic cybernetic system can be refined by the behavioral models developed in Section II, which evolves cybernetic technologies from the imperative and autonomic behaviors to the cognitive behaviors, as shown in Fig. 2.

Definition 18: The *entire behavior space of cybernetics* B_{CC} is a layered hierarchical structure that encompasses the imperative B_I, autonomic B_A, and cognitive B_C spaces from the bottom up, i.e.,

$$\begin{aligned} B_{CC} &\overset{\wedge}{=} (B_I, B_A, B_C) \\ &= \{ \quad (B_e, B_t, B_{\text{int}}) \qquad\qquad //B_I \\ &\qquad \|(B_e, B_t, B_{\text{int}}, B_g, B_d) \qquad //B_A \\ &\qquad \|(B_e, B_t, B_{\text{int}}, B_g, B_d, B_p, B_{\text{inf}}) //B_C \ \}. \end{aligned} \tag{15}$$

On the basis of Definition 18, a generic cybernetic system on the cognitive cybernetic space may be rigorously modeled as shown in Fig. 4. The *behavioral model* of a generic cybernetic system $\S_{\text{CS}}$ is an abstract logical model denoted by a set of parallel cognitive computing architectures and behaviors, where $\|$ denotes the parallel relation between given components of the system. The cybernetic system is logically abstracted as a set of process behaviors and underlying architectures and resources, such as memory, ports, system clock, system variables, and states. A cybernetic system's behavior in terms of a set of processes P_i is controlled and dispatched by the system $\S_{\text{CS}}$, which is triggered by various external or system events and needs, such as interrupts, goals, decisions, perceptions, and inferences.

Corollary 1: The three layers of the behavioral spaces B_I, B_A, and B_C obey the following relations:

$$B_I \subseteq B_A \subseteq B_C. \tag{16}$$

$$
\begin{array}{ll}
\multicolumn{2}{l}{\S_{\mathrm{CS}} \triangleq \mathrm{Cybernetic\_System}\mathbf{ST} ::} \\
\quad \{ \ \text{// System Architectures} & \\
\quad\quad < \mathop{R}\limits_{i\mathbf{N}=0}^{n_{proc}\mathbf{N}-1} P_i\mathbf{ST}> & \text{// Processes} \\
\quad\quad \| < \mathop{R}\limits_{addr\mathbf{P}=0}^{n_{MEM}\mathbf{H}-1} \mathrm{MEM}[\mathrm{ptr}\mathbf{P}]\mathbf{RT}> & \text{// Memory} \\
\quad\quad \| < \mathop{R}\limits_{ptr\mathbf{P}=0}^{n_{PORT}\mathbf{H}-1} \mathrm{PORT}[\mathrm{ptr}\mathbf{P}]\mathbf{RT}> & \text{// Ports} \\
\quad\quad \| <\S\mathrm{t}\mathbf{TM}> & \text{// The system clock} \\
\quad\quad \| < \mathop{R}\limits_{i\mathbf{N}=0}^{n_V\mathbf{N}-1} \mathrm{V_i}\mathbf{RT}> & \text{// System variables} \\
\quad\quad \| < \mathop{R}\limits_{i\mathbf{N}=0}^{n_S\mathbf{N}-1} \&\, \mathrm{S_i}\mathbf{BL}> & \text{// System statuses} \\
\quad \} & \\
\quad \| \{ \ \text{// System Behaviors} & \\
\quad\quad \| < \mathop{R}\limits_{k\mathbf{N}=0}^{n_e\mathbf{N}-1} @\mathrm{e_k}\mathbf{S} \hookrightarrow \mathrm{P_k}> & \text{// } \textit{Event}\text{-driven behaviors } (B_e) \\
\quad\quad \| < \mathop{R}\limits_{k\mathbf{N}=0}^{n_t\mathbf{N}-1} @\mathrm{t_k}\mathbf{TM} \hookrightarrow \mathrm{P_k}> & \text{// } \textit{Time}\text{-driven behaviors } (B_t) \\
\quad\quad \| < \mathop{R}\limits_{k\mathbf{N}=0}^{n_{\mathrm{int}}\mathbf{N}-1} @\mathrm{int_k}\odot \hookrightarrow \mathrm{P_k} > & \text{// } \textit{Interrupt}\text{-driven behaviors } (B_{int}) \\
\quad\quad \| < \mathop{R}\limits_{k\mathbf{N}=0}^{n_t\mathbf{N}-1} @\mathrm{g_k}\mathbf{ST} \hookrightarrow \mathrm{P_k}> & \text{// } \textit{Goal}\text{-driven behaviors } (B_g) \\
\quad\quad \| < \mathop{R}\limits_{k\mathbf{N}=0}^{n_t\mathbf{N}-1} @\mathrm{d_k}\mathbf{ST} \hookrightarrow \mathrm{P_k}> & \text{// } \textit{Decision}\text{-driven behaviors } (B_d) \\
\quad\quad \| < \mathop{R}\limits_{k\mathbf{N}=0}^{n_t\mathbf{N}-1} @\mathrm{p_k}\mathbf{ST} \hookrightarrow \mathrm{P_k}> & \text{// } \textit{Perception}\text{-driven behaviors } (B_p) \\
\quad\quad \| < \mathop{R}\limits_{k\mathbf{N}=0}^{n_{\mathrm{int}}\mathbf{N}-1} @\mathrm{inf_k}\mathbf{ST} \hookrightarrow \mathrm{P_k} > & \text{// } \textit{Inference}\text{-driven behaviors } (B_{inf}) \\
\quad \} &
\end{array}
$$

Fig. 4. Behavioral model of cybernetic systems.

Both Definition 18 and Corollary 1 indicate that any lower-layer CS is a subset of those of its higher layers. In other words, any higher-layer CS is a natural extension of those of lower layers, as shown in Fig. 2.

D. *Roles of Information in the Evolution of NI*

The profound uniqueness of cybernetics, CI, knowledge science, and intelligence science lies on the fact that its objects under study are located in a dual world as described in the following [25], [44], [46].

Definition 19: The *general worldview* of cybernetics, as shown in Fig. 5, reveals that the *natural world* (NW) is a dual encompassing both the *physical* (concrete) *world* (PW) and the *cyber* (abstract) *world* (CW).

In Fig. 5, there are four essences in modeling the NW, i.e., *matter* (M) and *energy* (E) for the PW, as well as *information* (I) and *intelligence* ($\mathfrak{I}$) for the abstract CW. In the IME-I model, the double arrows denote bidirectional relations between the essences in the CS, where known relations are denoted by solid lines, and relations yet to be discovered are denoted by dotted lines.

Definition 20: The IME-I model states that the NW, which forms the context of human and machine intelligence in cybernetics, is a dual. One aspect of it is the PW, and the other is the CW, where *intelligence* ($\mathfrak{I}$) plays a central role in the transformation between $I - M - E$.

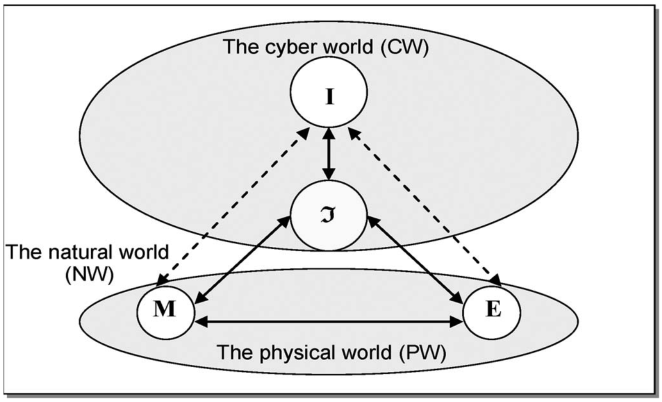


Fig. 5. IME-I model of cybernetics.

According to the IME-I model, information is the generic model for representing the abstract CW or the internal world of human beings. It is recognized that the basic evolutional need of mankind is to preserve both the species' biological traits and the cumulated information/knowledge bases. For the former, gene pools are adopted to pass human trait information via deoxyribonucleic acid (DNA) from generation to generation. However, for the latter, because acquired knowledge cannot be physiologically inherited between generations and individuals, various information means and systems are adopted to pass cumulated human information and knowledge.

It is noteworthy that intelligence ($\mathfrak{I}$) plays an irreplaceable role in the transformation between information, matter, and energy according to the IME-I model. It is observed that almost all cells in human bodies have a certain lifecycle in which they reproduce themselves via divisions. This mechanism allows human trait information to be transferred to the offspring through gene (DNA) replications during cell reproduction. However, it is observed that the most special mechanism of neurons in the brain is that they are the only type of cells in the human body that do not go through reproduction but remain alive throughout the entire human life [9], [32]. The advantage of this mechanism is that it enables the physiological representation and retention of acquired information and knowledge to be memorized in LTM. However, the key disadvantage of this mechanism is that it does not allow acquired information to be physiologically passed on to the next generation, because there is no DNA replication among memory neurons.

This physiological mechanism of neurons in the brain explains not only the foundation of memory and memorization but also the wonder why acquired information and knowledge cannot be passed and inherited physiologically from generation to generation. Therefore, to a certain extent, mankind relies very much on information on evolution than that of genes, because the basic characteristic of the human brain is intelligent information processing. In other words, the intelligent ability to cumulate and transfer information from generation to generation plays the vital role in mankind's evolution for both individuals and the entire species. This distinguishes human

TABLE II
APPROACHES TO IMPLEMENT NI AND AI

No.	Means	Approach	Category
1	Biological organisms	Naturally grown	NI
2	Silicon automata	Wired	AI
3	Computing systems	Programmed	AI
4	Other (in future)	Hybrid	NI + AI

beings from other species in natural evolution, where the latter cannot systematically pass acquired information by external and persistent information systems from generation to generation to enable it to grow cumulatively and exponentially.

IV. COMPUTATIONAL INTELLIGENCE FACET OF CYBERNETICS

Definition 21: Computational intelligence is a branch of cybernetics and AI that models human intelligence by computational methodologies and cognitively inspired models.

Intelligence is an important concept in cybernetics, CI, computing, and brain science [2], [4], [44], [51]. However, as reviewed in Section I, it was diversely perceived from different angles. A cybernetic perspective on natural and machine intelligence is focused on the transformation between *information, knowledge,* and *behavior*, where the nature of intelligence is the capability *to know* and *to do* what is possessed by both human brains and machine systems. In this view, a major objective of cybernetics is to answer the following.

1) How are the three forms of cognitive entities, i.e., information, knowledge, and behavior, transformed in the brain or a system?
2) What is the driving force to enable the transmissions?

A. GIM for Cybernetics

The abstract intelligence in general, and NI and AI in particular, can be classified into four categories, according to the variability between I/O to/from an intelligent system, known as the *routine, algorithmic, adaptive*, and *autonomic* intelligence from the bottom up. It is recognized that the basic approaches to implement intelligence can be classified as shown in Table II [46].

Definition 22: Intelligence, in the *narrow sense*, is a human or system ability that transforms information into behaviors, and in the *broad sense*, it is any human or system ability that autonomously transfers the forms of abstract information between *data*, *information*, *knowledge*, and *behaviors* in the brain.

According to Definition 22, NI is a set of intelligent behaviors possessed or implemented by human brains and those of other well-developed species. AI is intelligent behaviors possessed or implemented by machines or man-made systems.

The mechanisms of the NI can be described by a GIM as shown in Fig. 6. In the GIM 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). In the GIM model, any abstract object is physiologically retained in a particular type of memory, such as the SBM, STM, LTM, and ABM. These are the neural informatics foundation of NI and the physiological evidences of why NI can be classified into four forms as given in the following.

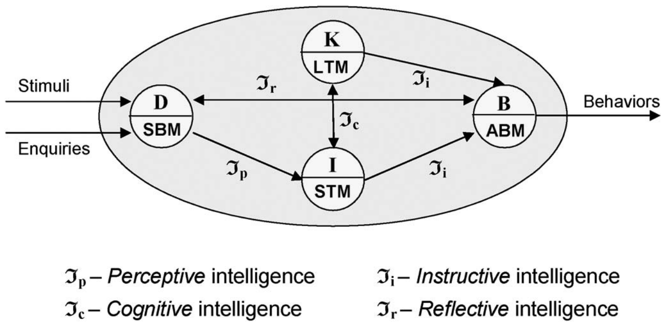


Fig. 6. GIM.

Definition 23: The *nature of intelligence* states that *intelligence* $\mathfrak{I}$ can be classified into four forms called *perceptive intelligence* $\mathfrak{I}_p$, *cognitive intelligence* $\mathfrak{I}_c$, *instructive intelligence* $\mathfrak{I}_i$, and *reflective intelligence* $\mathfrak{I}_r$, as modeled by

$$\begin{aligned} \Im \triangleq\; & \Im_{\mathrm{p}} : D \to I \text{ (Perceptive)} \\ & \| \Im_c : I \to K \text{ (Cognitive)} \\ & \| \Im_i : I \to B \text{ (Instructive)} \\ & \| \Im_r : D \to B \text{ (Reflective).} \end{aligned} \tag{17}$$

The four abstract objects can be rigorously described as follows.

Definition 24: The abstract object data D in GIM is a quantitative representation of external entities by a function r_d that maps an external message or signal M into a specific measurement scale S_k, i.e.,

$$\begin{aligned} D \triangleq\; & r_d : M \to S_k \\ & = \log_k M, \qquad k_{\min} = 2 \end{aligned} \tag{18}$$

where k is the base of the measurement scale, and the minimum of k, which is $k_{\min}$, is 2.

Definition 25: The abstract object *information* I in GIM is a perceptive interpretation of data by a function r_i that maps the data into a concept C, i.e.,

$$I \triangleq r_i : D \to C, \qquad r_i \in \Re \tag{19}$$

where $\Re$ is the set of relational operations of concept algebra with C as a *concept* in the form given as follows [46].

Definition 26: An *abstract concept* c on U, $c \sqsubseteq U$, is a 5-tuple, i.e.,

$$c \triangleq (O, A, R^c, R^i, R^o) \tag{20}$$

where

$\sqsubseteq$ denotes that a set or structure (tuple) is a substructure or derivation of another known structure;

O	nonempty set of objects of the concept $O = \{o_1, o_2, \ldots, o_m\} \subseteq \text{Þ}\, U$, where $\text{Þ}\, U$ denotes a power set of the universal set U;
A	nonempty set of attributes $A = \{a_1, a_2, \ldots, a_n\} \subseteq \text{Þ}\, M$, where M is the universal set of attributes of U;
$R^c \subseteq O \times A$	set of internal relations;
$R^i \subseteq A' \times A$	set of input relations, where $A' \sqsubseteq C' \wedge A \sqsubseteq c$, and C' is a set of external concepts $C' \subseteq \Theta_C$. For convenience, $R^i = A' \times A$ may simply be denoted as $R^i = C' \times c$;
$R^o \subseteq c \times C'$	set of output relations.

Definition 27: The abstract object *knowledge* K in GIM is a perceptive representation of information by a function r_k that maps a given concept C_0 into all related concepts, i.e.,

$$K \triangleq r_k : C_0 \rightarrow \left(\overset{n}{\underset{i=1}{\text{X}}} C_i \right), \qquad r_k \in \Re \tag{21}$$

where $\Re = \{\Rightarrow, \overset{+}{\Rightarrow}, \overset{-}{\Rightarrow}, \overset{\sim}{\Rightarrow}, \uplus, \pitchfork, \Lleftarrow, \vdash, \rightarrow\}$ [46].

Definition 28: The *entire knowledge* $\mathfrak{K}$ is represented by a *concept network*, which is a hierarchical network of concepts interlinked by the set of nine compositional operations $\Re$ defined in concept algebra, i.e.,

$$\mathfrak{K} = \Re : \overset{n}{\underset{i=1}{\text{X}}} C_i \rightarrow \overset{n}{\underset{j=1}{\text{X}}} C_j. \tag{22}$$

Definition 29: The abstract object *behavior* B in GIM is an embodied motivation M by a function r_b that maps a motivation M into an executable process P, i.e.,

$$\begin{aligned} B &\triangleq r_b : M \rightarrow P \\ &= \overset{m}{\underset{k=1}{\text{R}}} (@e_k \hookrightarrow P_k) \\ &= \overset{m}{\underset{k=1}{\text{R}}} \left[@e_k \hookrightarrow \overset{n-1}{\underset{i=1}{\text{R}}} (p_i(k) r_{ij}(k) p_j(k)) \right], \\ &\qquad\qquad j = i + 1;\ r_{ij} \in \Re_{\text{RTPA}} \end{aligned} \tag{23}$$

where M is generated by external stimuli or events and/or internal emotions or willingness, which are collectively represented by a set of events $E = \{e_1, e_2, \ldots, e_m\}$.

In Definition 29, P_k is represented by a set of cumulative relational subprocesses $p_i(k)$. The mathematical model of the cumulative relational processes may be referred to [46].

According to Definitions 22 and 23 in the context of the GIM model, the narrow sense of intelligence in cybernetics corresponds to the instructive and reflective intelligence, while the broad sense of intelligence in cybernetics includes all four forms of intelligence, i.e., the perceptive, cognitive, instructive, and reflective intelligence.

B. Compatibility of Natural and Machine Intelligence

Cybernetics and CI reveals the equivalence and compatibility between NI and AI. It is rational to perceive that NI should be well understood before AI may be studied on a rigorous basis. It also indicates that any machine that may implement a part of human behaviors and actions in information processing may be treated as possessing some extent of intelligence.

According to the GIM model, natural and machine (artificial) intelligence share the same CI foundation as described in the following, because the latter is a machine implementation of the former.

Corollary 2: The *compatible intelligent capability* states that NI and AI are compatible by sharing the same mechanisms of intelligent capability and behaviors, i.e.,

$$\text{AI} \cong \text{NI}. \tag{24}$$

At the logical level, the NI of the brain shares the same mechanisms as those of AI. The differences between NI and AI are only distinguishable by 1) the means of implementation and 2) the level of intelligent capability.

Corollary 3: The *inclusive intelligent capability* states that AI is a subset of NI, i.e.,

$$\text{AI} \subseteq \text{NI}. \tag{25}$$

Corollary 3 indicates that AI is dominated by NI. Therefore, one should not expect a computer or a software system to solve a problem where humans cannot. In other words, no AI or computer systems may be designed and/or implemented for a given problem where there is no solution collectively being known by human beings. Furthermore, Corollaries 2 and 3 explain that the development and implementation of AI rely on the understanding of the mechanisms and laws of NI in cybernetics.

On the basis of Corollary 2, it is recognized that the human brain, at the basic level, has no difference from those of other advanced animal species. However, the brain possesses unique advantages as identified in CI known as the quantitative and qualitative advantages. The former states that the magnitude of the memory capacity of the brain is tremendously greater than that of the closest species. The latter states that the possession of the abstract layer of memory and the abstract reasoning capacity makes the human brain fundamentally powerful in reasoning on the basis of the quantitative advantage.

Corollary 4: The *principal intelligent advantages* state that, on the basis of the two principal advantages with the *qualitative* and *quantitative* properties, humans gain the power as the most intelligent species in the world.

On the basis of Corollaries 1–4, the studies on NI and AI may be unified into a common framework in cybernetics and CI, where the fundamental models of GIM, LRMB [52], and OAR [44] play important roles in exploring the natural and machine intelligence.

It is noteworthy that the perception and inference of NI is carried out at the level of concepts, while that of machine intelligence is at the level of data and attribute information, which is lower than concept. Therefore, the new mathematical structure of concept algebra [47], [50] will provide a foundation for denoting and manipulating knowledge and formal inferences in the future-generation intelligent computers known as *cognitive computers* based on the improved understanding of the mechanisms of NI in cybernetics and CI.

V. CONCLUSION

This paper has explored the architecture, theoretical foundations, and engineering paradigms of contemporary cybernetics. Two cutting-edge facets of cybernetics known as CI and computational intelligence have been introduced in the cybernetic context. The GIM that provides a foundation to explain the mechanisms of the *perceptive*, *cognitive*, *instructive*, and *reflective intelligence* in cybernetics has been formally developed. It has been recognized that *abstract intelligence*, in the *narrow sense*, is a human or system ability that transfers information into behaviors, and in the *broad sense*, it is any human or system ability that autonomously transfers the forms of abstract information between *data*, *information*, *knowledge*, and *behaviors* in the brain. Based on the cybernetic models, a systematical reduction from the logical, functional, physiological, and biological levels has been delineated to form a coherent theory for the studies on natural and machine intelligence in cybernetics.

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