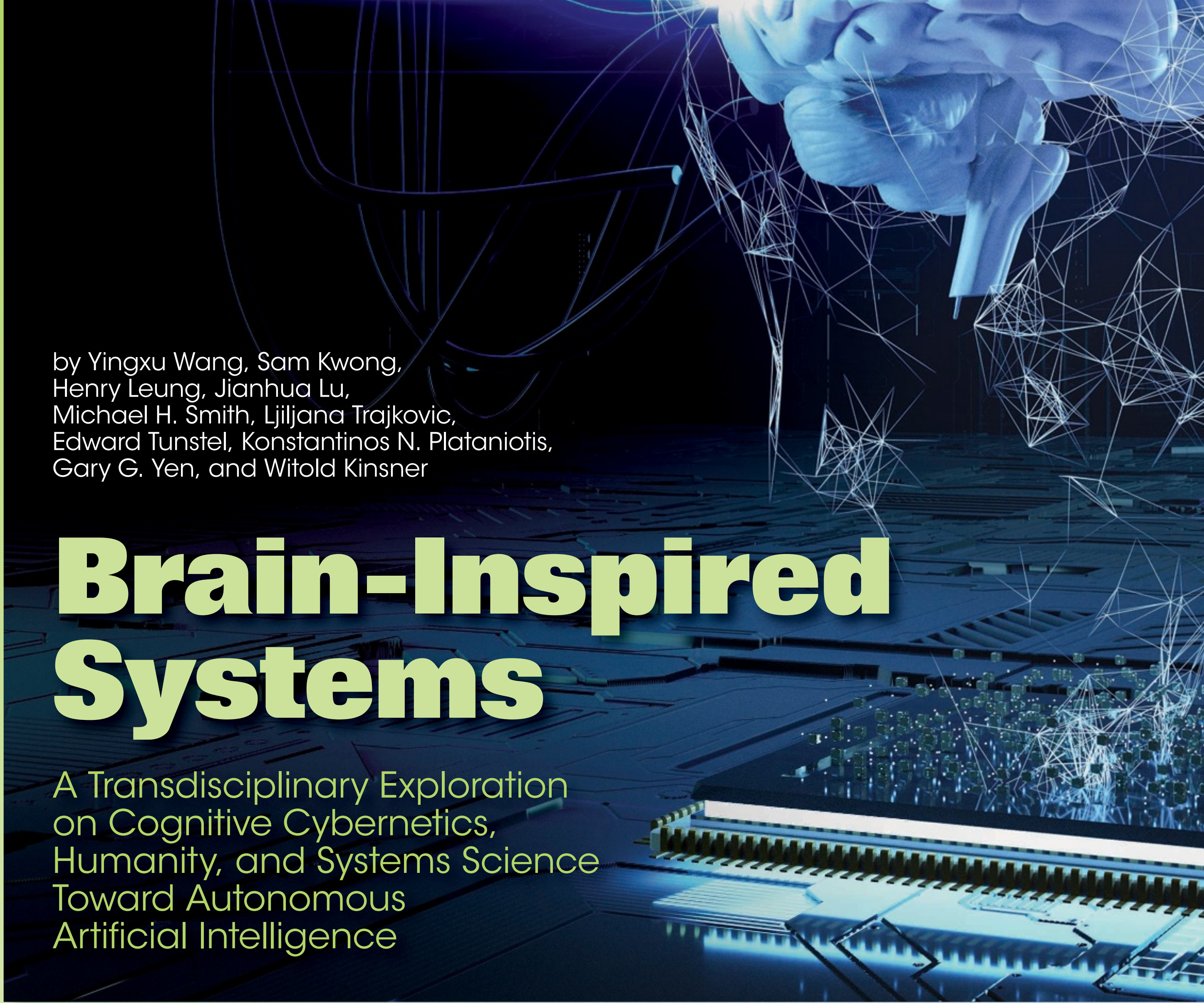

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Brain-Inspired Systems

A Transdisciplinary Exploration on Cognitive Cybernetics, Humanity, and Systems Science Toward Autonomous Artificial Intelligence

Brain-inspired cognitive systems (BCSs) are an emerging field of cybernetics, cognitive science, and system science. BCSs study not only the intelligence science foundations of artificial intelligence (AI) and cognitive systems, but also formal models of the brain embodied by computational intelligence. This article presents the brain and intelligence science foundations of BCS toward hybrid intelligent systems and the symbiotic intelligence of humanity. It explores the transdisciplinary theoretical foundations of system, brain, intelligence, knowledge, cybernetic, and cognitive sciences toward the next generation of knowledge processors beyond classic data processors for autonomous computing systems. A BCS provides an overarching platform for cognitive cybernetics, humanity, and systems to enable emerging hybrid societies shared by humans and intelligent machines.

Digital Object Identifier 10.1109/MSMC.2018.2889502
Date of current version: 15 January 2020

Cybernetics is perceived to be a transdisciplinary science of communication and control that mimics the brain as autonomous intelligent systems in the contexts of humans, animals, machines, organizations, and societies [22], [28], [32]. The IEEE Systems, Man, and Cybernetics Society (SMCS) leads an overarching field of studies [4], [20], [27] on the emergence of abstract sciences [24], [25], [34] as a counterpart of classic concrete sciences. The abstract sciences refer to contemporary data, information, knowledge, and intelligence sciences, as well as cybernetics, system science, sociology, and mathematics [34]. The classic concrete sciences encompass physics, chemistry, biology, neurology, physiology, and engineering sciences.

Brain science and its engineering simulations [6]–[9], [12], [13], [15], [18], [19], [23], [27], [30], [31], [33] are both classical and contemporary disciplines that study the functional and logical models of the brain, a set of cognitive processes of the mind, internal information-processing

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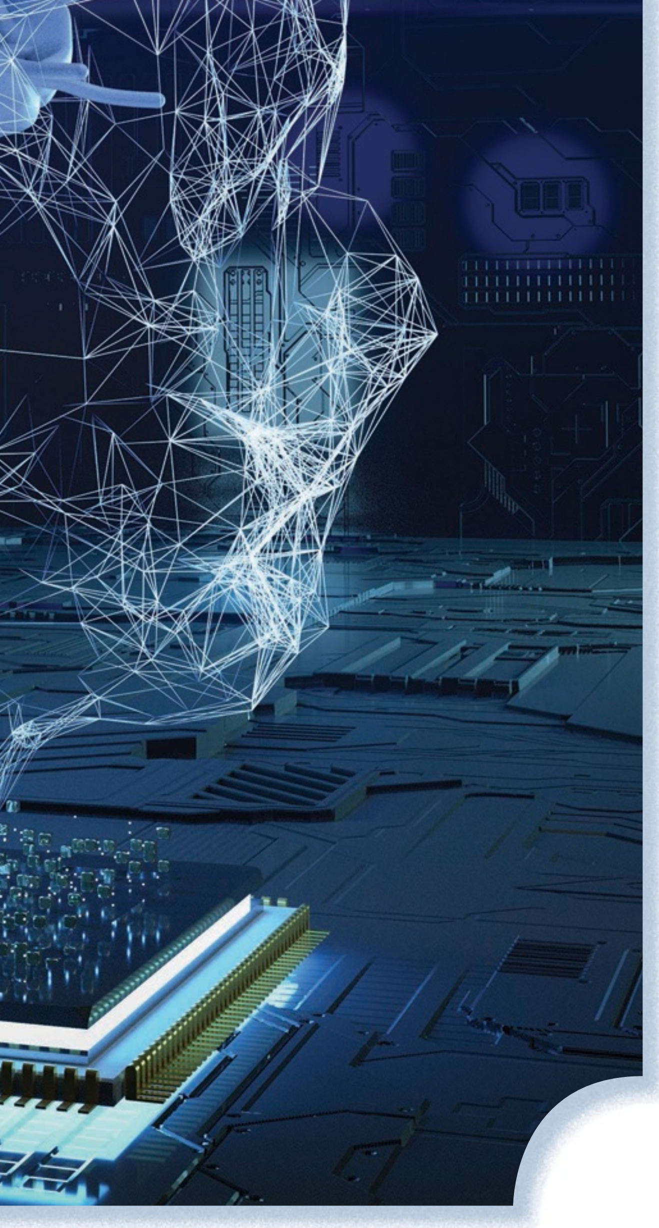

mechanisms, memories, consciousness, and their engineering applications. BCSs involve the cutting-edge field of intelligent systems based on transdisciplinary theoretical foundations of system, brain, intelligence, knowledge, and cybernetic and cognitive sciences, as well as denotational mathematics [1], [5], [6], [11], [18], [23], [26], [30]. A BCS is a synergy of hybrid human–machine systems in the context of cognitive cybernetics. Emerging paradigms of BCSs are the cognitive Internet of Things (IoT) and the Internet of Minds. These systems have paved the way to understand cybernetics and human brains as the last frontier of abstract science and novel engineering applications in autonomous, cognitive, and cybernetic systems.

All human-made sciences, technologies, and systems are perceived to be brain-driven and brain-inspired. Therefore, studies on the cognitive foundations of natural intelligence may shed light on the general mechanisms of various forms of intelligence toward pervasive BCS applications. Many important discoveries and innovative technologies are directly or indirectly inspired by the human brain, as it is perhaps the most matured intelligent system. Some well-known inventions in technologies and systems have been inspired by the brain, either intentionally or unintentionally, i.e., diodes, transistors, and artificial neural networks (Figure 1). Modern computers, AI, autonomous and cognitive systems, robots, and the IoT are typical BCS paradigms.

This article explores the theories and applications of BCSs that are underpinned by transdisciplinary studies in cognitive cybernetics, humanity, and system science. The neurological and cognitive foundations of BCSs, particularly the neural system model of consciousness as the kernel of natural intelligence and the cognitive model of the brain as the most complex system, are elaborated on in "The Neurological and Cognitive Foundations of the Brain" section, which describes the theory of abstract intelligence (aI) as the logical model of BCSs. "The Mission and Themes of TC-BCSs" section introduces the topics of the newly established IEEE SMCS Technical Committee on BCSs (TC-BCSs) toward an overarching study on contemporary BCSs, i.e., brain–machine systems, cognitive computers, cognitive robots, cognitive machine learning systems, cognitive neural networks, cognitive knowledge bases, semantic comprehension systems, big data systems, deep learning systems, intelligent unmanned systems, self-driving vehicles, cognitive IoTs, and hybrid human–machine systems.

The Neurological and Cognitive Foundations of the Brain

The brain as a highly matured intelligent system is an ideal reference model for revealing the theoretical foundations and general properties of AI. It explains that AI may or may not be constrained by the nature and expressive power of current mathematical methods for computational implementations.

Consciousness: The Kernel of Natural Intelligence

It is profound to consider the seat of consciousness and how it is generated in the brain as a highly complex cognitive mechanism of the mind based on its biological and physiological metabolism. Anatomical evidence [7], [19] has suggested the cerebellum stores memories and functions, as illustrated in Figure 2, even though they were not directly linked to the embodiment of consciousness. The cerebellum is then pinpointed as the seat of consciousness, represented by a cognitive map of the body [22], [30]. The cerebellum's anterior lobe is mainly responsible for representing and monitoring the entire body's status. However, the posterior lobe maintains the permanent skills acquired in the form of long-term procedural memory [9], [33].

The internal representation of human consciousness in the cerebellum (formally analyzed in [24]), is functionally recognized as the conscious status memory (CSM), a new type of human memory that supplements other memories, as formally described in the cognitive memory model (CMM) of the brain as a logical partition of the human

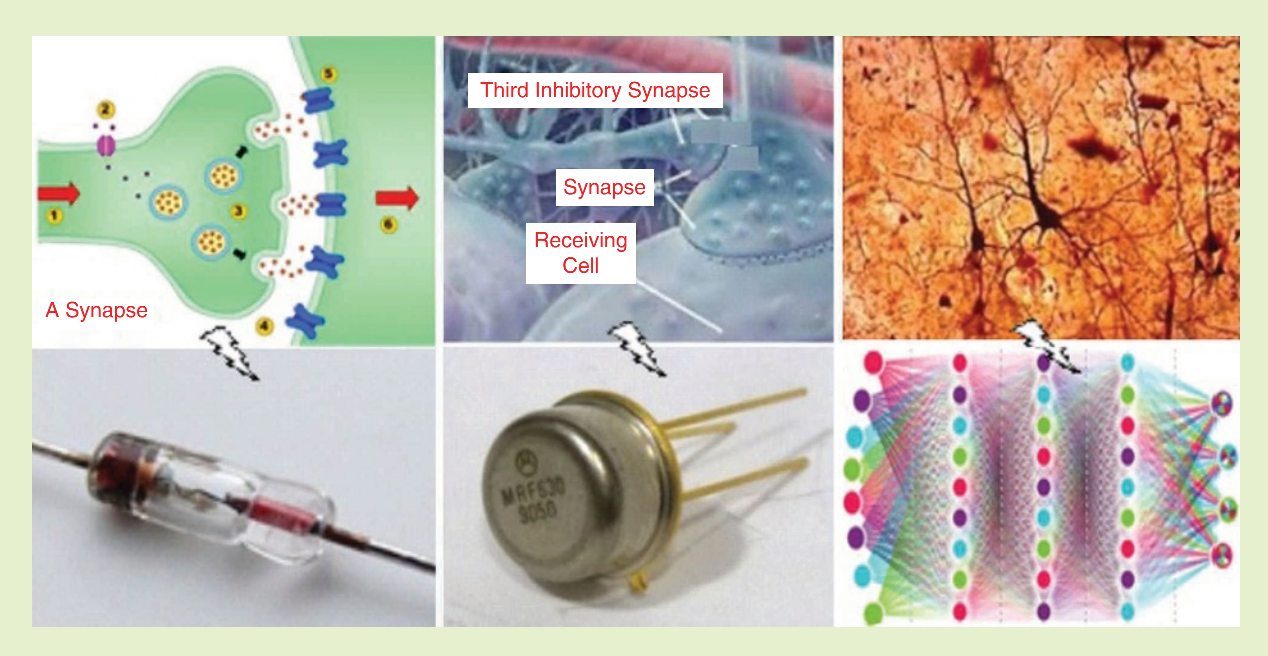

Figure 1. Paradigms of brain-inspired technologies and systems. (Top row) known brain neural structures and (bottom row) corresponding brain-inspired engineering devices and systems.

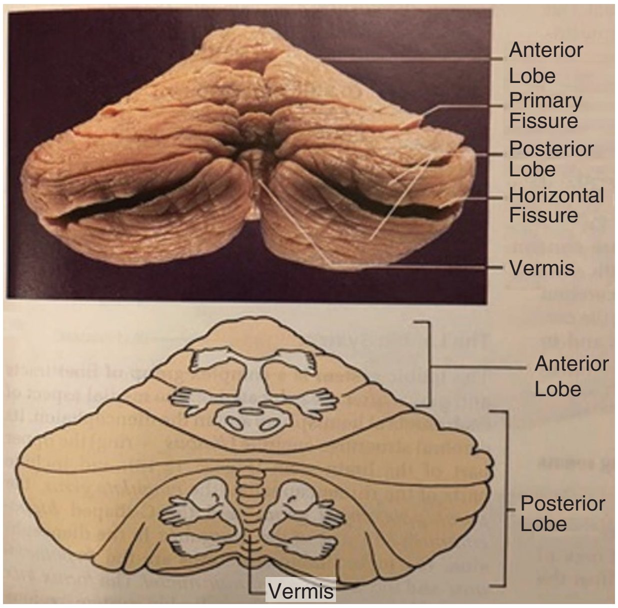

Figure 2. The cerebellum: the body's neurological map [7].

memory system in a parallel configuration (||) with five types of memories according to their functionalities:

$$\begin{aligned}\text{CMM} \triangleq (&\text{STM} && \text{// short-term memory}\\ \| &\text{LTM} && \text{// long-term memory}\\ \| &\text{SBM} && \text{// sensory buffer memory}\\ \| &\text{ABM} && \text{// action buffer memory}\\ \| &\text{CSM} && \text{// conscious status memory}). \end{aligned} \quad (1)$$

The logical view of consciousness is a collective mental state supplemented by attention and awareness, inductively generated from levels of metabolic homeostasis, unconsciousness, subconsciousness, and consciousness from the bottom up. Consciousness may also be deductively analyzed in a top-down approach through the cognitive levels mentioned earlier. It is noteworthy that most inherited life functions are subconscious or unconscious because, in contrast, most acquired life functions are conscious. Although we cannot intentionally control the subconscious or unconscious, either directly or indirectly, the conscious mind autonomously accesses it to carry out any cognitive function of the brain.

The mathematical model of consciousness Ξ may be formally described as a function f_c that maps a Cartesian product of the mental events (E) and the current status of the CSM into an updated state of the memory in CSM as

$$\Xi \triangleq f_c : E \times \text{CSM} \to \text{CSM}, \quad (2)$$

where the events stimulating the brain may be classified as external stimuli (S) or internal motivations (M), i.e., $E = S \cup M$.

Therefore, the external and internal subfunctions of consciousness, denoted by $f_{c\text{-}e}$ and $f_{c\text{-}i}$, respectively, may be formally expressed as

$$\begin{aligned}\text{CS} &\triangleq \begin{cases} f_{c\text{-}e} : S \times \text{CSM} \to \text{CSM} \\ f_{c\text{-}i} : M \times \text{CSM} \to \text{CSM} \end{cases}\\ &= f_c : \{S \cup M\} \times \text{CSM} \to \text{CSM}, \end{aligned} \quad (3)$$

where f_c represents the integrated external $(f_{c\text{-}e})$ and internal $(f_{c\text{-}i})$ consciousness for embodying the mechanisms of consciousness as the awareness of the status of the entire body registered in CSM. It is updated when either external stimuli or internal motivations are captured.

The conscious model of human selfhood embodied in CSM may explain many fundamental questions about the classic brain and mind issue. For instance, consciousness is equivalent to the brain's operating system (BOS) [22], [29], which monitors and controls all states of the brain, body, and internal/external environments, as well as the coherent interactions among them.

The Reference Model of the Brain and Brain-Inspired Systems

Since a computer may only be explained via reducing its logical models to low-level implementations in chips, a similar reductive mapping approach may be best for understanding the brain. A layered reference model of the brain (LRMB), which describes a logical architecture and the mechanisms of the brain, is introduced [30]. This logical model reveals that the brain may be formally embodied by 56 cognitive processes at seven layers and two subsystems, known as the subconscious and conscious mental functions. The subconscious encompasses the four lower-layer cognitive processes, for example, sensation, action, memory, and perception, that are equivalent to the BOS. Consciousness includes cognition, inference, and intelligence, the three higher-layer cognitive processes equivalent to the recurrent brain applications (BApp) built on the lower BOS layers.

According to LRMB, any human everyday life function or intelligent behavior may be perceived as a temporary composition of runtime instances by invoking the 56 cognitive processes across the seven layers. Therefore, the nature of intelligence may be rigorously reduced to other cognitive objects, i.e., data, information, knowledge, and wisdom acquired or generated in the brain [25].

A computational intelligence model (CIM) of the brain that simulates LRMB encompasses the processer, memory, consciousness monitor, sensory, and motor driver subsystems. Figure 3 illustrates and highlights these subsystems using different color schemes: the intelligent processor subsystem is indicated by blue links, memories in red, and other categories in green.

The CIM system model of the brain explains its key organs and their cognitive functions that are allocated in various regions of the brain, particularly the lobes and cortexes of the cerebrum and cerebellum. Systematic mapping between the logical (functional) and neurophysiological (structural) models of the brain is elaborated based on the

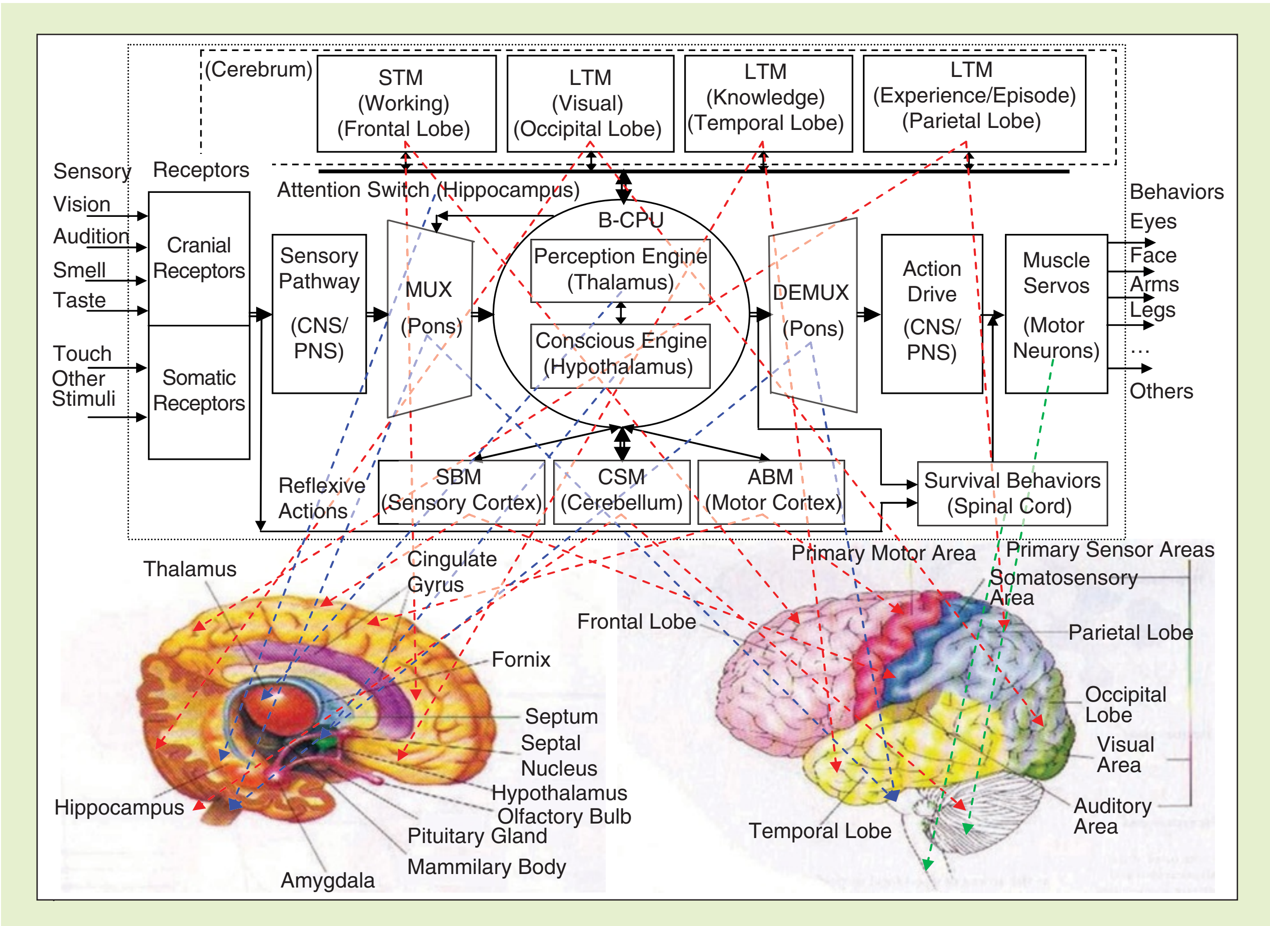

Figure 3. The computational intelligence model: mapping between the logical model of the brain and its neurological structures.

CIM, which efficiently reduces the extreme complexity to explain the structural and functional organs of the brain and their interactions. CIM and LRMB models provide a logical model for clarifying a set of conventionally overlapped and even contradicting empirical observations.

Both CIM and LRMB provide a blueprint for the emerging brain-inspired intelligence computers known as *cognitive computers* [29]. These computers transfer traditional data processing to knowledge processing, enabling the next generation of computing machines to fit human needs rather than requiring humans to fit the machines. The basic studies based on CIM will lead to cognitive computers that perceive, think, inference, and learn by mimicking the brain [22], [29].

A Theory of Abstract Intelligence

Underpinning Brain-Inspired Systems

Exploring and modeling the brain is recognized to be a highly recursive problem that remains a constant challenge to almost all scientific disciplines. A rigorous study of the cognitive foundations of natural intelligence may shed light on the general mechanisms of AI and computational intelligence toward pervasive BCS, explaining how intelligence is generated from neurophysiological structures.

Intelligence $(\dot{\mathbb{I}})$ is a human ability or a system function that transforms information (I) into behaviors (B) or knowledge (K) as

$$\dot{\mathbb{I}} \triangleq f_b : I \to B \parallel f_k : I \to K. \tag{4}$$

Cognitive informatics and cybernetics [22], [28], [31] reveal that natural intelligence may be explained by a hierarchical framework that maps the brain through the embodiments at neurological, physiological, cognitive, and logical layers from the bottom up. On the basis of exploring the cognitive mechanisms and neurophysiological structures of the brain in "The Neurological and Cognitive Foundations of the Brain" section, models for the general forms of intelligence and BCSs, which are known as the theory of αI, may be derived. αI is a mathematical model of the core properties across all forms of natural intelligence and AI.

In the theory of αI, the hierarchy of cognitive objects $\varkappa$ represented in the human brain is a four-tuple in the categories of data $(\mathbb{D})$, $\mathbb{I}$, $\mathbb{K}$, and $\dot{\mathbb{I}}$ from the bottom up, according to their levels of abstraction:

$$\varkappa \triangleq (\mathbb{D}, \mathbb{I}, \mathbb{K}, \dot{\mathbb{I}}) = \begin{cases} \mathbb{D} = f_d : O \to Q \\ \mathbb{I} = f_i : D \to S \\ \mathbb{K} = f_k : I \to C \\ \dot{\mathbb{I}} = f_i : I \to B \end{cases}, \tag{5}$$

where the symbols denote object (O), quantity (Q), semantics (S), concept (C), and behavior (B), respectively.

Let $\varkappa^0$ through $\varkappa^4$ be the hierarchical layers of human cognitive objects in the brain corresponding to $\mathbb{D}$, $\mathbb{I}$, $\mathbb{K}$, and $\dot{\mathbb{I}}$, respectively. The relationship between the cognitive objects in the brain may be formalized in the following principle.

Transformability among the cognitive objects, $\varkappa = (\mathbb{D}, \mathbb{I}, \mathbb{K}, \dot{\mathbb{I}})$, in the brain is a recursive structure S_Ξ:

$$\begin{aligned} S_\Xi &= \mathop{R}_{k=4}^{1} \varkappa^k(\varkappa^{k-1}), \quad \varkappa^0 = \mathop{R}_{i=0}^{n} d_i \,|\, \mathbb{T}_i \\ &= \varkappa^4(\varkappa^3(\varkappa^2(\varkappa^1(\varkappa^0)))) \\ &= \dot{\mathbb{I}}\Big(\mathbb{K}\Big(\mathbb{I}\Big(\mathbb{D}\Big(\mathop{R}_{i=0}^{n} d_i \,|\, \mathbb{T}_i\Big)\Big)\Big)\Big), \end{aligned} \tag{6}$$

where the terminal structure at the bottom layer of the hierarchical framework is given as n-dimensional data, $\boldsymbol{R}_{i=0}^{n} d_i|\mathbb{T}_i$ where $|\mathbb{T}_i$ denotes the ith suffix of data type for data object d_i.

Based on (6), the framework of αI may be embodied by the four types of intelligence: perceptive $(\dot{\mathbb{I}}_p)$, cognitive $(\dot{\mathbb{I}}_c)$, instructive $(\dot{\mathbb{I}}_i)$, and reflexive $(\dot{\mathbb{I}}_r)$.

$$\alpha I \triangleq (\dot{\mathbb{I}}_p, \dot{\mathbb{I}}_c, \dot{\mathbb{I}}_i, \dot{\mathbb{I}}_r) = \begin{cases} \dot{\mathbb{I}}_p = f_p : D \to I & \text{// perceptive} \\ \dot{\mathbb{I}}_c = f_c : I \to K & \text{// cognitive} \\ \dot{\mathbb{I}}_i = f_i : I \to B & \text{// instructive} \\ \dot{\mathbb{I}}_r = f_r : D \to B & \text{// reflexive} \end{cases}, \tag{7}$$

where specific forms of cognitive objects and associated memories in the brain have been defined in (1) and (5), respectively. Behavior (B) denotes a type of cognitive process that transfers an abstract stimulus to an observable action.

The αI theory reveals that the structures and configurations of a human memory system may be modeled as being logically classified into the categories of sensory buffer memory (SBM), short-term memory (STM), long-term memory (LTM), action buffer memory (ABM), and CSM. Therefore, certain cognitive entities, i.e., data, information, knowledge, and intelligence, are embodied in different memories on the basis of the CMM model as given in (1): SBM(D), STM(I), LTM(K), CSM$(\dot{\mathbb{I}})$, and ABM$(\dot{\mathbb{I}})$, respectively.

Based on LRMB, the structural model of the brain (SMB) as an autonomous intelligence system encompasses a set of parallel interactions between the natural intelligent system (NIS) and the CMM, as well as the lower structures underpinning them:

$$\begin{aligned} \text{SMB} &\triangleq \text{NIS} \parallel \text{CMM} \\ &= (\text{BOS} \| \text{BApp}) \parallel (\text{STM} \| \text{LTM} \| \text{SBM} \| \text{ABM} \| \text{CSM}), \end{aligned} \tag{8}$$

where BOS and BApp represents the brain's operating system and applications of NIS, respectively.

SMB reveals the relationship between NIS and CMM, where NIS serves the natural intelligent engine and CMM is essential to enable NIS to function properly. In other words, although memory is not the central power of the brain or any AI system, it is a necessary foundation due to no memory, no intelligence, according to the αI and LRMB theories.

The αI theory provides a foundation to enable a multidisciplinary enquiry of the brain and intelligence science. To better explain the architectures and functions of the brain, as well as their intricate relations and interactions, systematic logical models become indispensable across

Table 1. The themes of the Technical Committee on Brain-Inspired Cognitive Systems.

Autonomous Systems	Cognitive Systems	Cybernetic Systems
Natural intelligent systems	Cognitive computers	Cognitive cybernetics
Big neural data systems	Computational intelligent systems	Cognitive IoT
Neuroinformatic systems	Cognitive machine learning	Cognitive robots
Neural knowledge bases	Cognitive sensors and networks	Hybrid human–machine societies
Neural image processing systems	Machine knowledge learning systems	Cognitive informatics
Symbiotic and collective intelligent systems	Natural language comprehension systems	Human–machine sharable knowledge bases
Neurocomputing systems	Intelligent unmanned systems	Human–machine symbiosis

the transdisciplinary studies at levels of neurology, physiology, cognition, and denotational mathematics [2], [3], [10], [14], [16], [17], [21], [23], [26], [31]–[33].

The Mission and Themes of TC-BCS

The TC-BCSs within the IEEE SMCS were established in 2018. The current challenges to cognitive cybernetics and the increasing demands for brain-inspired systems in society, industry, and education have advanced BCS studies toward integrating hybrid human–machine systems. BCSs provide an overarching link among the three principle technical areas of the IEEE SMCS based on the rapid advances of AI, human–machine systems/societies, brain-inspired computational intelligence, and autonomous/unmanned systems.

The mission of TC-BCSs is to promote interdisciplinary and transdisciplinary theories, methodologies, best practices, and engineering/societal applications of brain-inspired and cognitive cybernetic systems. TC-BCSs synergize transdisciplinary theoretical foundations of system, brain, intelligence, cybernetic, and cognitive sciences, focusing on hybrid human–machine and brain-inspired systems, as well as their societal implications.

The themes of TC-BCSs include, but are not limited to, a rich set of research subjects, as summarized in Table 1. The research and activities of TC-BCS may be classified into the categories of autonomous, cognitive, and cybernetic systems across SMC technical areas of cybernetics, human–machine systems, and systems science and engineering. TC-BCSs will not only cover a coherent theme of the IEEE SMCS on cognitive cybernetics but also establish an emerging and unique field of BCSs.

TC-BCSs strive to serve the interests and demands of researchers, practitioners, policy makers, and the general public on the frontier of brain-inspired systems. Their strategic goals are to address the cutting-edge studies of brain-inspired systems in cognitive cybernetics and novel engineering implementations. The TC-BCSs will strengthen the well-positioned leadership of SMCS in the strategic fields of brain-inspired, cognitive, autonomous, and unmanned systems. They will establish active collaboration among several IEEE Societies including those of the SMCS, Computer, Computational Intelligence, and Robotics and Automation, as well as the International Institute of Cognitive Informatics and Cognitive Computing and leading industrial partners.

Conclusion

It is recognized that the brain and natural intelligence should be well understood before AI can be developed on a rigorous basis. BCSs study not only the brain to innovate AI and cognitive systems but also the formal models and rigorous theories necessary for explaining and simulating the brain. We presented the latest developments in basic studies and engineering applications of BCSs toward novel human–machine systems and intelligent cybernetic systems. Establishing TC-BCSs will enhance BCS research and engineering applications in AI, computational intelligence, cognitive systems, cognitive computers, cognitive robots, autonomous systems, machine learning systems, cognitive neural networks, semantic comprehension systems, cognitive IoTs, big data systems, intelligent unmanned systems, self-driving vehicles, and hybrid human–machine systems.

Acknowledgment

We would like to acknowledge the advice and support from the IEEE System, Man, and Cybernetics Society vice presidents, including Andreas Nuernberger, Rodney Roberts, and Vladik Kreinovich, as well as Stuart Rubin for establishing the technical committee on brain-inspired cognitive systems. We would also like to thank the late Prof. Mo E. El-Hawary and *IEEE Systems, Man, and Cybernetics Magazine* Associate Editor Haibin Zhu for their valuable advice.

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References

[1] J. Albus, "Outline for a theory of intelligence," *IEEE Trans. Syst., Man, Cybern.*, vol. 21, no. 3, pp. 473–509, 1991.

[2] D. Daniel and T. Dean, "Neural networks and neuroscience-inspired computer vision," *Curr. Biol.*, vol. 24, no. 18, pp. 921–929, 2015.

[3] M. Helmstaedter, "The mutual inspirations of machine learning and neuroscience," *Neuron*, vol. 86, no. 1, pp. 25–28, 2015.

[4] "Mission of IEEE Systems, Man, and Cybernetics Society." Accessed on: Dec. 1, 2018. [Online]. Available: http://www.ieeesmc.org/

[5] J. M. I, "Computational intelligence," in R. A. Wilson and C. K. Frank, Eds., *The MIT Encyclopedia of the Cognitive Sciences*, Cambridge, MA: MIT Press, 1999, pp. i73–i80.

[6] L. Larger, A. Baylón-Fuentes, R. Martinenghi, V. S. Udaltsov, Y. K. Chembo, and M. Jacquot, "A faster brain-inspired computer," *Nature*, vol. 542, p. 394, Feb. 2017.

[7] K. Li, S. Kwong, Q. Zhang, and K. Deb, "Interrelationship-based selection for decomposition multiobjective optimization," *IEEE Trans. Cybern.*, vol. 45, no. 10, pp. 2076–2088, 2015.

[8] L. Li, N.-N. Zheng, and F.-Y. Wang, "On the crossroad of artificial intelligence: A revisit to Alan Turing and Norbert Wiener," *IEEE Trans. Cybern.*, vol. 49, no. 10, pp. 3618–3626, Oct. 2019.

[9] E. N. Marieb, *Human Anatomy and Physiology*, 2nd ed. Redwood City, CA: Benjamin Cummings, 1992.

[10] J. McCarthy, M. L. Minsky, N. Rochester, and C. E. Shannon, "A Proposal for the Dartmouth Summer Research Project on Artificial Intelligence, August 31, 1955," *AI Mag.*, vol. 27, no. 4, winter 2006. doi: 10.1609/aimag.v27i4.1904.

[11] R. A. Miranda et al., "DARPA-funded efforts in the development of novel brain-computer interface technologies," *J. Neurosci. Meth.*, vol. 244, pp. 52–67, Apr. 2015.

[12] F. L. Nathan, V. Paul, and J. P. Tony, "The state of the art in biomimetics," *Bioinspir. Biomim*, vol. 8, p. 013001, Mar. 2013.

[13] A. Novellino, P. D'Angelo, L. Cozzi, M. Chiappalone, V. Sanguineti, and S. Martinoia, "Connecting neurons to a mobile robot: An in vitro bidirectional neural interface," *Comput. Intell. Neurosci*, vol. 7, no. 2, p. 12725, 2007.

[14] R. Pashaie et al., "Closed-loop optogenetic brain interface," *IEEE Trans. Biomed. Eng.*, vol. 62, no. 10, pp. 2327–2337, 2015.

[15] G. Ruffini, F. Wendling, I. Merlet, B. Molaee-Ardekani, A. Mekonnen, and R. Salvador, "Transcranial current brain stimulation: Models and technologies," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 21, no. 3, pp. 333–345, 2013.

[16] S. Ruiz, K. Buyukturkoglu, M. Rana, N. Birbaumer, and R. Sitaram, "Real-time FMRI brain computer interfaces: Self-regulation of single brain regions to networks," *Biol. Psychol.*, vol. 95, pp. 4–20, Jan. 2014.

[17] J. L. Shobe, L. D. Claar, S. Parhami, K. I. Bakhurin, and S. C. Masmanidis, "Brain activity mapping at multiple scales with silicon microprobes containing 1,024 electrodes," *J. Neurophysiol.*, vol. 114, no. 3, pp. 2043–2052, 2015.

[18] R. L. Solso, Ed., *Mind and Brain Sciences in the 21th Century*. Cambridge, MA: MIT Press, 1999.

[19] R. J. Sternberg, *In Search of the Human Mind*. New York: Harcourt Brace Jovanovich, 1998.

[20] E. Tunstel, "Systems, man, and cybernetics society synergies," *IEEE Syst. Man Cybern. Mag.*, vol. 5, no.1, p. 4, Jan. 2018.

[21] S. Vassanelli and M. Mahmud, "Trends and challenges in neuroengineering: Toward 'intelligent' neuroprostheses through brain-'brain inspired systems' communication," *Front. Neurosci.*, vol. 10, p. 438, Sept. 2016.

[22] Y. Wang, "On cognitive informatics," *Brain Mind*, vol. 4, no. 2, pp. 151–167, 2003.

[23] Y. Wang et al., "Cognitive intelligence: Deep learning, thinking, and reasoning with brain-inspired systems," *Int. J. Cogn. Inform. Natural Intell.*, vol. 10, no. 4, pp. 1–21, 2016.

[24] Y. Wang, "Towards the abstract system theory of system science for cognitive and intelligent systems," *Springer J. Complex Intell. Syst.*, vol. 1, nos. 1–4, pp. 1–22, 2015.

[25] Y. Wang, "Formal cognitive models of data, information, knowledge, and intelligence," *WSEAS Trans. Comput.*, vol. 14, pp. 770–781, June 2015.

[26] Y. Wang, "In search of denotational mathematics: Novel mathematical means for contemporary intelligence, brain, and knowledge sciences," *J. Adv. Math. Appl.*, vol. 1, no. 1, pp. 4–25, 2012.

[27] Y. Wang and G. Fariello, "On neuroinformatics: Mathematical models of neuroscience and neurocomputing," *J. Adv. Math. Appl*, vol. 1, no. 2, pp. 206–217, 2012.

[28] Y. Wang, W. Kinsner, and D. Zhang, "Contemporary cybernetics and its faces of cognitive informatics and computational intelligence," *IEEE Trans. Syst., Man, Cybern. B, Cybern.*, vol. 39, no. 4, pp. 823–833, 2009.

[29] Y. Wang, "On cognitive computing," *Int. J. Softw. Sci. Comput. Intell.*, vol. 1, no. 3, pp. 1–15, 2009.

[30] Y. Wang, Y. Wang, S. Patel, and D. Patel, "A layered reference model of the brain (LRMB)," *IEEE Trans. Syst., Man, and Cybern. C, Appl. Rev.*, vol. 36, no. 2, pp. 124–133, 2006.

[31] Y. Wang, "Keynote: Cognitive foundations and formal theories of human and robot visions," in *17th IEEE Int. Conf. Cognitive Informatics & Cognitive Computing (ICCI*CC'18)*. Berkeley, CA: IEEE Comput. Soc. Press, July 2018, p. 5.

[32] N. Wiener, *Cybernetics or Control and Communication in the Animal and the Machine*. Cambridge, MA: MIT Press, 1948.

[33] R. A. Wilson and C. K. Frank, Eds., *The MIT Encyclopedia of the Cognitive Sciences*. Cambridge, MA: MIT Press, 2001.

[34] Y. Wang and E. Tunstel, "The emergence of abstract sciences and transdisciplinary advances developments in systems, man, and cybernetics," *IEEE Syst., Man, Cybern. Mag*, vol. 5, no. 2, p. 12–19, Apr. 2019.

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