

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.

Manuscript received January 9, 2008; revised December 20, 2008. This work was supported in part by the Natural Sciences and Engineering Research Council of Canada. This paper was recommended by Guest Editor M. Huber.

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Digital Object Identifier 10.1109/TSMCB.2009.2013721

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], [44] [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

79 to accomplish one's goals and those of society. Lefton *et al.* [27]
 80 defined intelligence as the overall capacity of the individual
 81 to act purposefully, to think rationally, and to deal effectively
 82 with the social and cultural environment. They perceived that
 83 intelligence is not a thing, but a process that is affected by
 84 a person's experiences in the environment. Wang's *abstract*
 85 *intelligent theory* (αI) [44], [51] revealed that NI is the driving
 86 force that transforms cognitive information in the forms of
 87 data, knowledge, skill, and behavior. A *Layered Reference*
 88 *Model of the Brain* (LRMB) has been developed [52], which
 89 encompasses 43 cognitive processes at seven layers known
 90 as the *sensation, memory, perception, action, metacognitive,*
 91 *metainference,* and *higher cognitive layers* from the bottom up.
 92 The development of classic and contemporary cybernet-
 93 ics, cognitive informatics (CI), and the cross fertilization be-
 94 tween computer science, system science, computer/software
 95 engineering, neuropsychology, and computational intelligence
 96 have led to a wide range of interesting new research fields
 97 known as CI [44], [45], [47], [49], [51], [54], [55]. CI is an
 98 interdisciplinary research field that tackles the fundamental
 99 problems of modern cybernetics, information science, systems
 100 science, computer/software engineering, computational intelli-
 101 gence, cognitive science, neuropsychology, and life sciences.
 102 Almost all of the hard problems yet to be solved in the afore-
 103 mentioned areas share a common root in the understanding of
 104 the mechanisms of the NI and cognitive processes of the brain.
 105 Therefore, CI is perceived as a new frontier that explores the
 106 internal information processing mechanisms of the brain and
 107 their engineering applications in cybernetics, computing, and
 108 information technology industry.

109 This paper attempts to explore the theoretical foundations
 110 and engineering paradigms of contemporary cybernetics, par-
 111 ticularly its newly developed facets known as CI and com-
 112 putational intelligence. In the remainder of this paper, the
 113 contemporary architecture of cybernetics and its hierarchical
 114 behavior model at the imperative, autonomic, and cognitive
 115 layers are elaborated in Section II. The CI facet of cybernetics
 116 is presented in Section III, which explains how the brain may be
 117 mimicked in cybernetics via CI. The computational intelligence
 118 facet of cybernetics is described in Section IV, which presents
 119 the generic intelligence model (GIM) of cybernetics and an-
 120 alyzes the compatibility between the natural and cybernetic
 121 intelligence. As a result, a coherent framework of contem-
 122 porary cybernetics is elaborated toward the development of
 123 interdisciplinary and transdisciplinary theories and application
 124 paradigms in cybernetics, CI, and computational intelligence.

125 II. CONTEMPORARY ARCHITECTURE OF CYBERNETICS

126 Studies in cybernetics cover biologically, cognitively, and
 127 intelligently motivated computational paradigms [5], [15], [21],
 128 [31], [40], [51] such as abstract intelligence, neural networks,
 129 genetic algorithms, fuzzy systems, autonomic systems, cogni-
 130 tive systems, robotics, CI, and computational intelligence.

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

A. Domain of Cybernetics

135

The domain and architecture of contemporary cybernetics 136
 encompass a wide range of coherent fields, as shown in Fig. 1, 137
 from the machine, natural, and organizational intelligence to 138
 social intelligence in the horizontal scopes and from the logical, 139
 functional, and cognitive models to neural (biological) models 140
 in the vertical reductive hierarchy. Therefore, cybernetics in 141
 nature is a multidisciplinary and transdisciplinary inquiry of 142
 cognitive information processing and autonomic systems. 143

As shown in Fig. 1, the double arrows indicate abstraction/ 144
 reduction or aggregation/specification. The scope of contempo- 145
 rary cybernetics in the horizontal domains has been extended 146
 from mainly machine intelligence to natural, organizational, 147
 and societal intelligence. In the vertical dimension, the reduc- 148
 tion levels of cybernetics have been extended from logical and 149
 functional models to cognitive and neural models. 150

With the notion of *functional reductionism*, a logical model 151
 of the NI is needed to explain formally the high-level mecha- 152
 nisms of the brain on the basis of observations at the biological 153
 and physiological levels. The logical model of the brain is 154
 the highest level of abstraction for explaining its cognitive 155
 mechanisms. Based on it, a systematical reduction from the 156
 logical, functional, physiological, and biological levels may be 157
 established in both the top-down and bottom-up approaches, 158
 which will enable the establishment of a coherent theory of NI 159
 and cybernetics. 160

It is noteworthy that, at the overall level, contemporary 161
 cybernetics has evolved from pure autonomic communica- 162
 tion and control theories to CI [44], [45] and computa- 163
 tional intelligence [22]. The former provides an extended NI 164
 and internal information-processing perspective to cybernetics, 165
 while the latter studies a computation modeling perspective to 166
 cybernetics. 167

B. Behavioral Spaces of Cybernetics

168

Behaviorism is a doctrine of psychology and CI that studies 169
 the association between a given stimulus and an observed 170
 response of human brains and cybernetic systems [45], [52]. 171
 CI reveals that human and machine behaviors may be classi- 172
 fied into four categories known as the *perceptive, cognitive,* 173
instructive, and *reflective* behaviors [46]. 174

The behavioral space of cybernetics and cybernetic systems 175
 can be classified into the imperative, autonomic, and cognitive 176
 cyberspaces (CSs), as shown in Fig. 2. The *imperative CS* is 177
 an enclosure of instructive and passive behaviors. The *auto-* 178
nomic CS is an enclosure of internally motivated behaviors 179
 beyond those of the imperative space. The *cognitive CS* is an 180
 enclosure of perceptive and inference-driven behaviors beyond 181
 those of both imperative and autonomic spaces. More formal 182
 descriptions of the three forms of CSs will be presented in 183
 Section II-B2, after each layer of the hierarchical CSs and their 184
 basic properties is formally modeled as follows. 185

1) *Behavioral Models of Cybernetics:* Before the elabora- 186
 tion of the behavioral spaces of cybernetics, the taxonomies of 187
 cybernetic behaviors at different layers of cybernetics, as shown 188
 in Fig. 2, are formally modeled in the following. 189

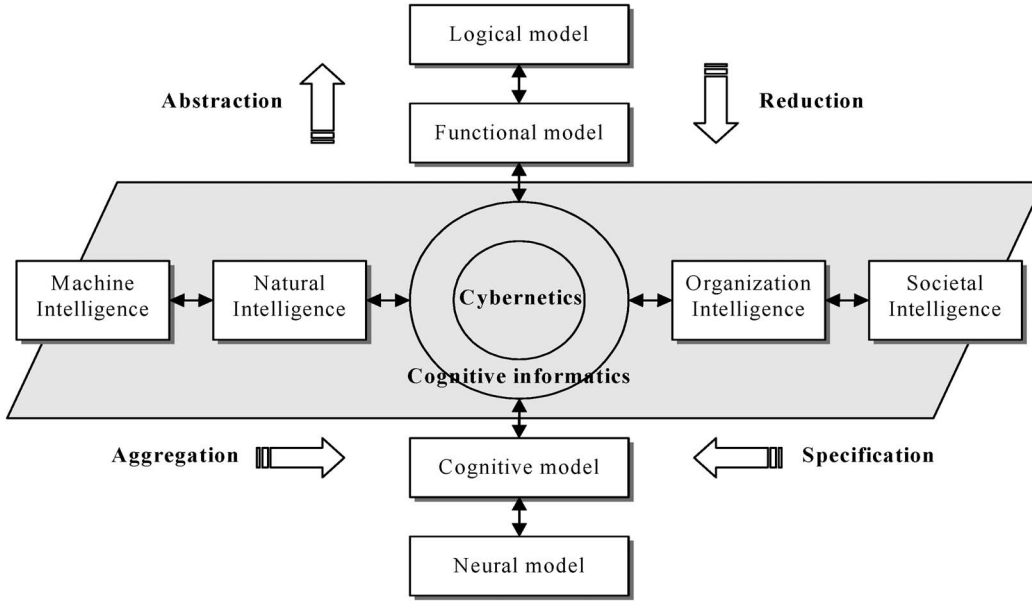


Fig. 1. Architecture of contemporary cybernetics and CI.

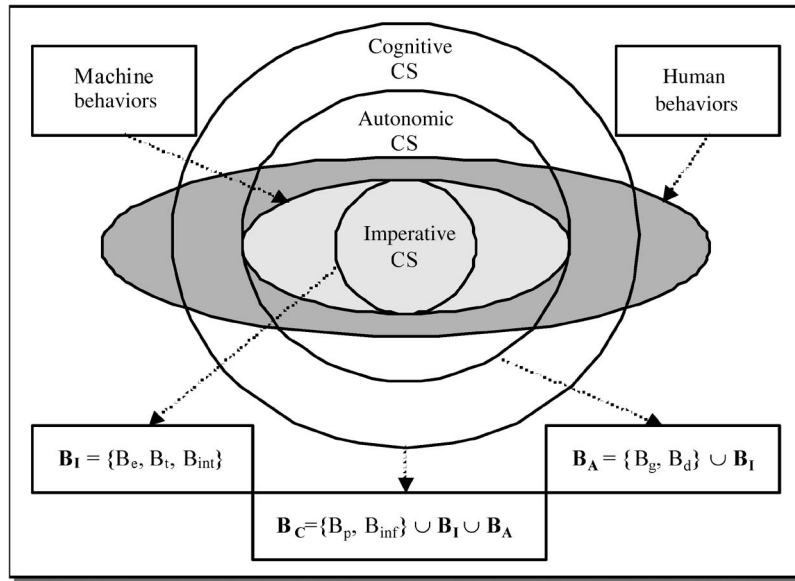


Fig. 2. Behavioral spaces of cybernetics.

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

194 The types of events that may trigger a behavior can be
 195 classified into operational ($@eS$), time ($@tTM$), and interrupt
 196 ($@int \odot$) events, where $@$ is the *event prefix*, and S , TM , and
 197 \odot are three of the type suffixes, respectively. The *interrupt*
 198 *event* is a kind of special event that models the interruption
 199 of an executing process, the temporal handover of controls to
 200 an interrupt service routine, and the return of control after its
 201 completion.

202 *Definition 3:* An *interrupt*, which is denoted by \downarrow , is a paral-
 203 lel process relation in which a running process P is temporarily
 204 held by another higher-priority process Q via an interrupt
 205 event ($@int \odot$) at the interrupt point \odot , and the interrupted

process will be resumed when the high-priority process has
 206 been completed, i.e.,
 207

$$P \downarrow Q \stackrel{\wedge}{=} P \parallel (@int \odot \nearrow Q \searrow \odot) \quad (1)$$

where \nearrow and \searrow denote an *interrupt service* and an *interrupt*
 208 *return*, respectively.
 209

In general, all types of events, including the operational,
 210 timing, and interrupt events, are captured by the system to
 211 dispatch a designated behavior.
 212

Definition 4: An *event-driven behavior* B_e , which is denoted
 213 by \hookrightarrow_e , is an imperative process in which the i th behavior in
 214 terms of a designated process P_i is triggered by a predefined
 215 event $@e_i S$, i.e.,
 216

$$B_e \stackrel{\wedge}{=} \bigwedge_{i=1}^n (@e_i S \hookrightarrow_e P_i) \quad (2)$$

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

220 *Definition 5:* A time-driven behavior B_t , which is denoted
221 by \leftarrow_t , is an imperative process in which the i th behavior in
222 terms of process P_i is triggered by a predefined point of time
223 $@t_i\mathbf{TM}$, i.e.,

$$B_t \triangleq \bigwedge_{i=1}^n \mathbf{R} (@t_i\mathbf{TM} \leftarrow_t P_i) \quad (3)$$

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

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

$$B_{\text{int}} \triangleq \bigwedge_{i=1}^n \mathbf{R} (@int_i \odot \leftarrow_{\text{int}} P_i). \quad (4)$$

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

$$B_g \triangleq \bigwedge_{i=1}^n \mathbf{R} (@g_i\mathbf{ST} \leftarrow_g P_i). \quad (5)$$

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

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

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

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

240 *Definition 9:* A decision-driven behavior B_d , which is de-
241 noted by \leftarrow_d , is an autonomic process in which the i th behavior
242 in terms of process P_i is generated by a given decision $@d_i\mathbf{ST}$,
243 i.e.,

$$B_d \triangleq \bigwedge_{i=1}^n \mathbf{R} (@d_i\mathbf{ST} \leftarrow_d P_i). \quad (7)$$

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

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

$$\begin{aligned} d &= f(\mathcal{A}, C) \\ &= f : \mathcal{A} \times C \rightarrow \mathcal{A}, \quad \mathcal{A} \neq \emptyset. \end{aligned} \quad (8)$$

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

$$B_p \triangleq \bigwedge_{i=1}^n \mathbf{R} (@p_i\mathbf{PC} \leftarrow_p P_i) \quad (9)$$

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

In Definition 11, the *perception result* $p\mathbf{PC}$ is an outcome 254
of the cognitive process of perception that transforms sensory 255
data in the sensory buffer memory (SBM) into interpreted 256
information in the short-term memory (STM) of the brain in 257
the same form as that of a goal. 258

Definition 12: An inference-driven behavior B_{inf} , which is 259
denoted by \leftarrow_{inf} , is a cognitive process in which the i th behavior 260
in terms of process P_i is generated by the result of an inference 261
process $@inf_i\mathbf{PC}$, i.e., 262

$$B_{\text{inf}} \triangleq \bigwedge_{i=1}^n \mathbf{R} (@inf_i\mathbf{PC} \leftarrow_{\text{inf}} P_i) \quad (10)$$

where formal inferences can be classified into the *deductive*, 263
inductive, *abductive*, and *analogical* categories, as well as 264
modal, probabilistic, and belief theories [46]. 265

The *inference behavior* is the second extension of the cog- 266
nitive CS on top of the imperative and autonomic CSs, which 267
is a cognitive process that reasons about a possible causality 268
from given premises based on known causal relations between 269
a pair of cause and effect proven true by empirical arguments, 270
theoretical inferences, or statistical regulations. 271

2) *Hierarchy of Cybernetic Behavioral Spaces:* The hierar- 272
chy of cybernetic behavioral spaces, as shown in Fig. 2, can be 273
divided into the imperative, autonomic, and cognitive spaces of 274
cybernetic behaviors. Conventional computing machines only 275
cover the imperative CS. Computational intelligence [22] and 276
adaptive systems extend the CS from the imperative to the 277
autonomic ones. However, it covers little in the cognitive CS. 278
CI and cognitive computers [46] encompass the entire domain 279
of cybernetics and CSs, mainly the higher-level cognitive be- 280
haviors, such as those of perception and inference in both 281
intelligent cybernetic systems and the brain. 282

Definition 13: The *imperative behavioral space* of cybernet- 283
ics B_I is a set of instruction-triggered behaviors such as the 284
event-driven behaviors (B_e), time-driven behaviors (B_t), and 285
interrupt-driven behaviors (B_{int}), i.e., 286

$$B_I \triangleq \{B_e, B_t, B_{\text{int}}\}. \quad (11)$$

An imperative system implemented on B_I may do nothing 287
unless a specific program is loaded, in which the stored program 288
transfers a general-purpose computer to a specific intelligent 289
application. The imperative system is a traditional and passive 290
system that implements deterministic, context-free, and stored- 291
program-controlled behaviors. 292

Definition 14: The *autonomic behavioral space* of cyber- 293
netics B_A is a set of internally motivated and autonomously 294
generated behaviors such as the goal-driven behaviors (B_g) and 295
decision-driven behaviors (B_d) on the basis of the imperative 296
space B_I , i.e., 297

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

An autonomic system implemented on B_A extends the pas- 298
sive and imperative cybernetic system on B_I to nondetermin- 299
istic, context-dependent, and adaptive behaviors, such as the 300
goal- and decision-driven behaviors [16], [23]. The autonomic 301
systems do not rely on instructive and procedural information 302

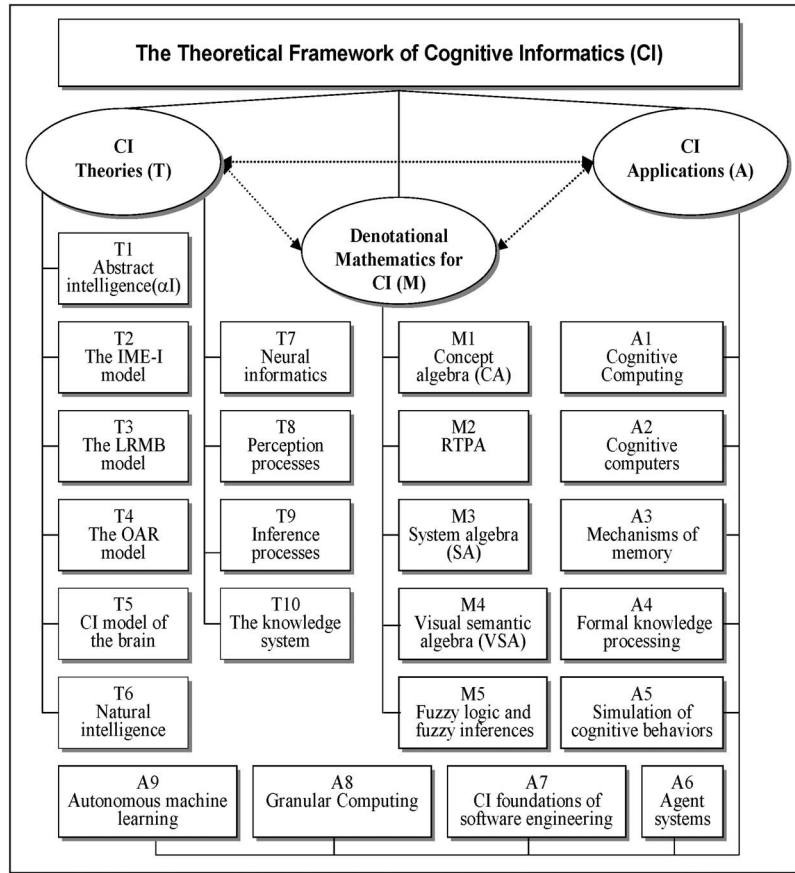


Fig. 3. Theoretical framework of CI.

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

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

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

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

III. CI FACET OF CYBERNETICS

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

Definition 16: CI is a transdisciplinary inquiry of cyber- 324
netics, cognitive science, computer science, and information 325
sciences that investigates into the internal information process- 326
ing mechanisms and processes of the brain and NI, and their 327
engineering applications via an interdisciplinary approach. 328

A. Theoretical Framework of CI

329

The structure of the theoretical framework of CI [44] is 330
shown in Fig. 3, which covers ten fundamental theories such 331
as *abstract intelligence* [51], the *information–matter–energy–* 332
intelligence (IME-I) model, the LRMB, the *object–attribute–* 333
relation (OAR) model of internal information representation 334
in the brain, the CI model (CIM) of the brain, the mechanism 335
of NI, neural informatics, the mechanism of human perception 336
processes, the cognitive processes of formal inferences, and the 337
formal knowledge system. 338

Four forms of denotational mathematics [46]–[50], such as 339
concept algebra, *real-time process algebra (RTPA)*, *system* 340
algebra, and *visual semantic algebra* are created in CI, 341
which enable a rigorous treatment of knowledge and behavior 342
representations and manipulations in a formal and coherent 343
framework. The new structures of denotational mathematics 344
have extended the abstract objects that are under study in 345
mathematics to a higher level, encompassing abstract concepts, 346
behavioral processes, abstract systems, and visual semantic 347
patterns beyond conventional mathematical entities such as 348
numbers, sets, relations, functions, lattices, and groups. 349

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

350 A wide range of applications of the descriptive mathematics
351 in the context of CI have been identified, as shown in Fig. 3,
352 particularly the cognitive computing methodologies and cogni-
353 tive computer systems [24], [44], [45], mechanisms of human
354 memory, simulation of the cognitive behaviors of the brain,
355 autonomous agent systems, CI foundations of software engi-
356 neering, granular computing [28], [34], [35], [37], [53], [61]–
357 [63], and autonomous machine learning. The latest advances in
358 CI have led to the development of cognitive computers, which
359 extends computing techniques from imperative to cognitive
360 computing that implements higher-level computing behaviors
361 in the cognitive CS, as given in Definition 15.

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

375 B. Taxonomy of Cognitive Information in the Brain

376 Almost all modern disciplines of science and engineering
377 deal with information and knowledge. However, data, informa-
378 tion, and knowledge are conventionally considered as different
379 entities in the literature [7], [60]. Based on the investigations
380 in CI, particularly the research on the OAR model [44] and the
381 mechanisms of internal information representation, the empiri-
382 cal classification of data, information, and knowledge may be
383 revised. A CI theory on the relationship among data (sensa-
384 tional inputs), actions (behavioral outputs), and their internal
385 representations such as knowledge, experience, and skill is that
386 they are generally different forms of information. These forms
387 of cognitive information may be classified based on how the
388 internal information relates to the inputs and outputs (I/O) of
389 the brain, as shown in Table I, which is known as the CIM.

390 According to the CIM, the taxonomy of cognitive infor-
391 mation is determined by types of I/O of information to and
392 from the brain, where both I/O can either be information or
393 action. For a given cognitive process, if both I/O are abstract
394 information, the internal information acquired is *knowledge*,
395 if both I/O are empirical actions, the type of internal in-

formation is *skill*, and the remainder combinations between 396
action/information and information/action produce *experience* 397
and *behaviors*, respectively. In Table I, behavior is a new 398
type of cognitive information modeled inside the brain, which 399
embodies an abstract input to an observable behavioral output. 400

Definition 17: The generic forms of cognitive information 401
state that there are four categories of internal information \mathcal{I} in 402
the brain known as *knowledge* (K), *behaviors* (B), *experience* 403
(E), and *skills* (S), i.e., 404

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

It is noteworthy that the approaches to acquire 405
knowledge/behavior and experience/skills are fundamentally 406
different. Although knowledge or behaviors may directly 407
and indirectly be acquired, skills and experiences can only 408
be obtained directly by hands-on activities. Furthermore, the 409
associated memories of the abstract information are different, 410
where knowledge and experience are retained as abstract 411
relations in long-term memory (LTM), while behaviors and 412
skills are retained as wired neural connections in action buffer 413
memory (ABM) [44]. 414

C. Behavioral Model of Cybernetic Systems 415

The basic architecture of a generic cybernetic system can 416
be refined by the behavioral models developed in Section II, 417
which evolves cybernetic technologies from the imperative 418
and autonomic behaviors to the cognitive behaviors, as shown 419
in Fig. 2. 420

Definition 18: The entire behavior space of cybernetics 421
 B_{CC} is a layered hierarchical structure that encompasses the 422
imperative B_I , autonomic B_A , and cognitive B_C spaces from 423
the bottom up, i.e., 424

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

On the basis of Definition 18, a generic cybernetic system on 425
the cognitive cybernetic space may be rigorously modeled as 426
shown in Fig. 4. The *behavioral model* of a generic cybernetic 427
system \S_{CS} is an abstract logical model denoted by a set of par- 428
allel cognitive computing architectures and behaviors, where \parallel 429
denotes the parallel relation between given components of the 430
system. The cybernetic system is logically abstracted as a set of 431
process behaviors and underlying architectures and resources, 432
such as memory, ports, system clock, system variables, and 433
states. A cybernetic system's behavior in terms of a set of 434
processes P_i is controlled and dispatched by the system \S_{CS} , 435
which is triggered by various external or system events and 436
needs, such as interrupts, goals, decisions, perceptions, and 437
inferences. 438

Corollary 1: The three layers of the behavioral spaces B_I , 439
 B_A , and B_C obey the following relations: 440

$$B_I \subseteq B_A \subseteq B_C. \quad (16)$$

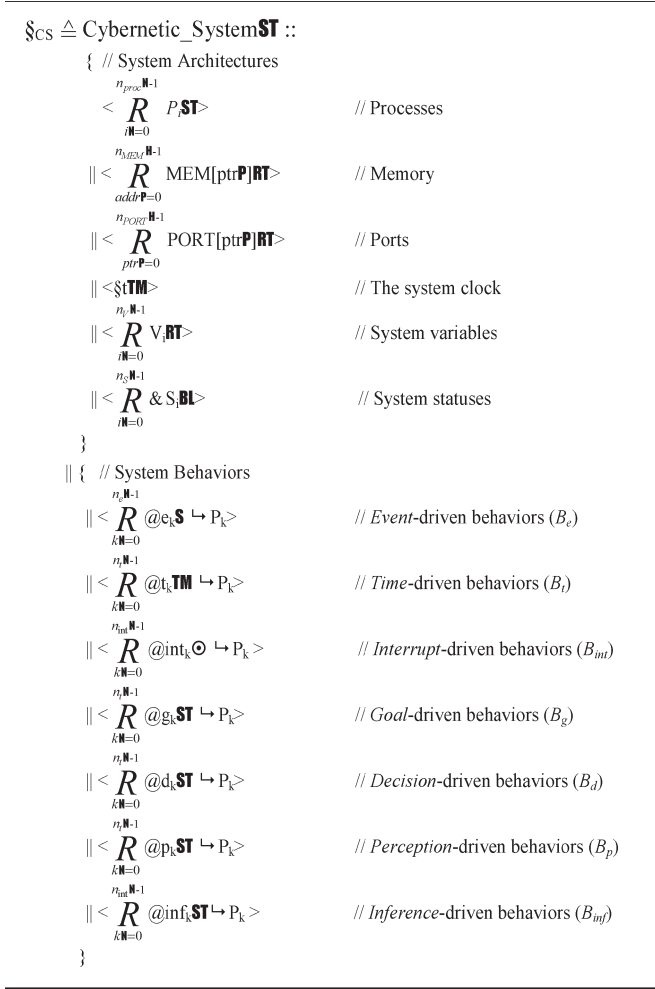


Fig. 4. Behavioral model of cybernetic systems.

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.

4.4.5 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 (J) 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 cy-

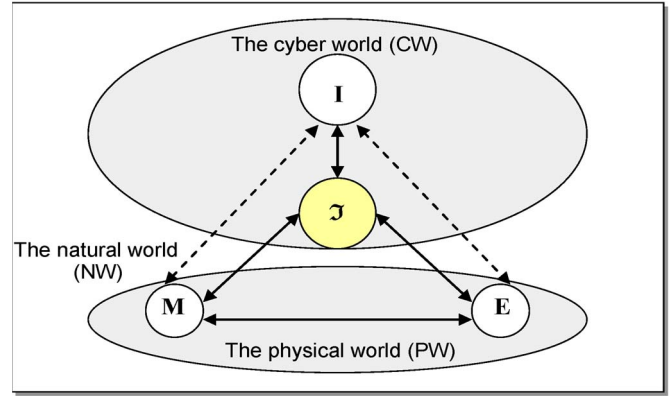


Fig. 5. IME-I model of cybernetics.

bernetics, is a dual. One aspect of it is the PW, and the other is the CW, where intelligence (J) plays a central role in the transformation between I–M–E.

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 evolutionary 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 (J) 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

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

509 IV. COMPUTATIONAL INTELLIGENCE 510 FACET OF CYBERNETICS

511 *Definition 21: Computational intelligence* is a branch of
512 cybernetics and AI that models human intelligence by compu-
513 tational methodologies and cognitively inspired models.

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

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

527 A. GIM for Cybernetics

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

535 *Definition 22: Intelligence*, in the *narrow sense*, is a human
536 or system ability that transforms information into behaviors,
537 and in the *broad sense*, it is any human or system ability that au-
538 tonomously transfers the forms of abstract information between
539 *data*, *information*, *knowledge*, and *behaviors* in the brain.

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

545 The mechanisms of the NI can be described by a GIM
546 as shown in Fig. 6. In the GIM model, different forms of
547 intelligence are described as a driving force that transfers
548 between a pair of abstract objects in the brain such as data
549 (D), information (I), knowledge (K), and behavior (B). In the

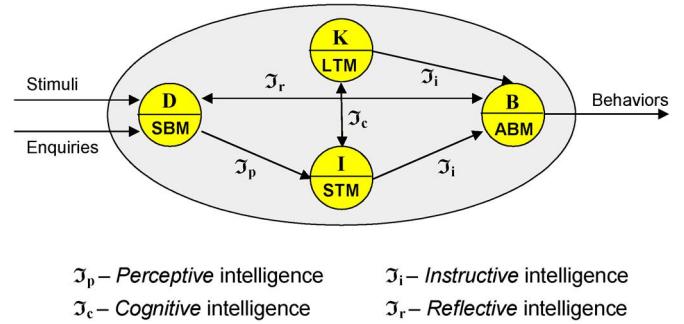


Fig. 6. GIM.

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.

Definition 23: The nature of intelligence states that *intelli-*
gence \mathcal{I} can be classified into four forms called *perceptive in-*
telligence \mathcal{J}_p , *cognitive intelligence* \mathcal{J}_c , *instructive intelligence*
 \mathcal{J}_i , and *reflective intelligence* \mathcal{J}_r , as modeled by

$$\begin{aligned} \mathfrak{S} &\stackrel{\Delta}{=} \mathfrak{S}_p : D \rightarrow I \text{ (Perceptive)} \\ &\|\mathfrak{S}_c : I \rightarrow K \text{ (Cognitive)} \\ &\|\mathfrak{S}_i : I \rightarrow B \text{ (Instructive)} \\ &\|\mathfrak{S}_r : D \rightarrow B \text{ (Reflective)}. \end{aligned} \quad (17)$$

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.,

$$\begin{aligned} D &\stackrel{\Delta}{=} r_d : M \rightarrow S_k \\ &= \log_k M, \quad k_{\min} = 2 \end{aligned} \quad (18)$$

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.,

$$I \stackrel{\Delta}{=} r_i : D \rightarrow C, \quad r_i \in \mathfrak{R} \quad (19)$$

where \mathfrak{R} 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.,

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

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

578 O nonempty set of objects of the concept $O =$
 579 $\{o_1, o_2, \dots, o_m\} \subseteq \mathfrak{P}U$, where $\mathfrak{P}U$ denotes
 580 a power set of the universal set U ;
 581 A nonempty set of attributes $A = \{a_1, a_2, \dots,$
 582 $a_n\} \subseteq \mathfrak{P}M$, where M is the universal set of
 583 attributes of U ;
 584 $R^c \subseteq O \times A$ set of internal relations;
 585 $R^i \subseteq A' \times A$ set of input relations, where $A' \sqsubseteq C' \wedge A \sqsubseteq$
 586 c , and C' is a set of external concepts $C' \sqsubseteq$
 587 Θ_C . For convenience, $R^i = A' \times A$ may
 588 simply be denoted as $R^i = C' \times c$;
 589 $R^o \subseteq c \times C'$ set of output relations.

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

$$K \triangleq r_k : C_0 \rightarrow \left(\bigtimes_{i=1}^n C_i \right), \quad r_k \in \mathfrak{R} \quad (21)$$

593 where $\mathfrak{R} = \{\Rightarrow, \overset{\pm}{\Rightarrow}, \Rightarrow, \Rightarrow, \uplus, \upharpoonright, \Leftarrow, \vdash, \rightarrow\}$ [46].

594 *Definition 28:* The *entire knowledge* \mathfrak{K} is represented by a
 595 *concept network*, which is a hierarchical network of concepts
 596 interlinked by the set of nine compositional operations \mathfrak{R} de-
 597 fined in concept algebra, i.e.,

$$\mathfrak{K} = \mathfrak{R} : \bigtimes_{i=1}^n C_i \rightarrow \bigtimes_{j=1}^n C_j. \quad (22)$$

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

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

601 where M is generated by external stimuli or events and/or inter-
 602 nal emotions or willingness, which are collectively represented
 603 by a set of events $E = \{e_1, e_2, \dots, e_m\}$.

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

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

613 B. Compatibility of Natural and Machine Intelligence

614 Cybernetics and CI reveals the equivalence and compatibility
 615 between NI and AI. It is rational to perceive that NI should be
 616 well understood before AI may be studied on a rigorous basis.
 617 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. 618 619

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. 620 621 622 623

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., 624 625 626

$$\text{AI} \cong \text{NI}. \quad (24)$$

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. 627 628 629 630

Corollary 3: The *inclusive intelligent capability* states that
 AI is a subset of NI, i.e., 631 632 633

$$\text{AI} \subseteq \text{NI}. \quad (25)$$

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 com-
 puter 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. 634 635 636 637 638 639 640

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. 641 642 643 644 645 646 647 648 649 650

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. 651 652 653 654

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. 655 656 657 658 659

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 infer-
 ences in the future-generation intelligent computers known as
cognitive computers based on the improved understanding of
 the mechanisms of NI in cybernetics and CI. 660 661 662 663 664 665 666 667 668

669 V. CONCLUSION

670 This paper has explored the architecture, theoretical foun-
 671 dations, and engineering paradigms of contemporary cyber-
 672 netics. Two cutting-edge facets of cybernetics known as CI
 673 and computational intelligence have been introduced in the
 674 cybernetic context. The GIM that provides a foundation to
 675 explain the mechanisms of the *perceptive, cognitive, instruc-*
 676 *tive, and reflective intelligence* in cybernetics has been formally
 677 developed. It has been recognized that *abstract intelligence*, in
 678 the *narrow sense*, is a human or system ability that transfers
 679 information into behaviors, and in the *broad sense*, it is any
 680 human or system ability that autonomously transfers the forms
 681 of abstract information between *data, information, knowledge,*
 682 and *behaviors* in the brain. Based on the cybernetic models, a
 683 systematical reduction from the logical, functional, physiologi-
 684 cal, and biological levels has been delineated to form a coherent
 685 theory for the studies on natural and machine intelligence in
 686 cybernetics.

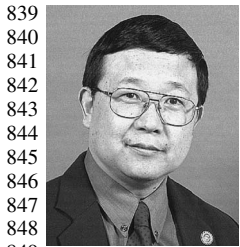
687 ACKNOWLEDGMENT

688 The authors would like to thank the anonymous reviewers for
 689 their valuable comments and suggestions.

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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.

Manuscript received January 9, 2008; revised December 20, 2008. This work was supported in part by the Natural Sciences and Engineering Research Council of Canada. This paper was recommended by Guest Editor M. Huber.

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Digital Object Identifier 10.1109/TSMCB.2009.2013721

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], [44] [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

79 to accomplish one's goals and those of society. Lefton *et al.* [27]
 80 defined intelligence as the overall capacity of the individual
 81 to act purposefully, to think rationally, and to deal effectively
 82 with the social and cultural environment. They perceived that
 83 intelligence is not a thing, but a process that is affected by
 84 a person's experiences in the environment. Wang's *abstract*
 85 *intelligent theory* (αI) [44], [51] revealed that NI is the driving
 86 force that transforms cognitive information in the forms of
 87 data, knowledge, skill, and behavior. A *Layered Reference*
 88 *Model of the Brain* (LRMB) has been developed [52], which
 89 encompasses 43 cognitive processes at seven layers known
 90 as the *sensation, memory, perception, action, metacognitive,*
 91 *metainference,* and *higher cognitive layers* from the bottom up.
 92 The development of classic and contemporary cybernet-
 93 ics, cognitive informatics (CI), and the cross fertilization be-
 94 tween computer science, system science, computer/software
 95 engineering, neuropsychology, and computational intelligence
 96 have led to a wide range of interesting new research fields
 97 known as CI [44], [45], [47], [49], [51], [54], [55]. CI is an
 98 interdisciplinary research field that tackles the fundamental
 99 problems of modern cybernetics, information science, systems
 100 science, computer/software engineering, computational intelli-
 101 gence, cognitive science, neuropsychology, and life sciences.
 102 Almost all of the hard problems yet to be solved in the afore-
 103 mentioned areas share a common root in the understanding of
 104 the mechanisms of the NI and cognitive processes of the brain.
 105 Therefore, CI is perceived as a new frontier that explores the
 106 internal information processing mechanisms of the brain and
 107 their engineering applications in cybernetics, computing, and
 108 information technology industry.

109 This paper attempts to explore the theoretical foundations
 110 and engineering paradigms of contemporary cybernetics, par-
 111 ticularly its newly developed facets known as CI and com-
 112 putational intelligence. In the remainder of this paper, the
 113 contemporary architecture of cybernetics and its hierarchical
 114 behavior model at the imperative, autonomic, and cognitive
 115 layers are elaborated in Section II. The CI facet of cybernetics
 116 is presented in Section III, which explains how the brain may be
 117 mimicked in cybernetics via CI. The computational intelligence
 118 facet of cybernetics is described in Section IV, which presents
 119 the generic intelligence model (GIM) of cybernetics and an-
 120 alyzes the compatibility between the natural and cybernetic
 121 intelligence. As a result, a coherent framework of contem-
 122 porary cybernetics is elaborated toward the development of
 123 interdisciplinary and transdisciplinary theories and application
 124 paradigms in cybernetics, CI, and computational intelligence.

125 II. CONTEMPORARY ARCHITECTURE OF CYBERNETICS

126 Studies in cybernetics cover biologically, cognitively, and
 127 intelligently motivated computational paradigms [5], [15], [21],
 128 [31], [40], [51] such as abstract intelligence, neural networks,
 129 genetic algorithms, fuzzy systems, autonomic systems, cogni-
 130 tive systems, robotics, CI, and computational intelligence.

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

A. Domain of Cybernetics

135

The domain and architecture of contemporary cybernetics 136
 encompass a wide range of coherent fields, as shown in Fig. 1, 137
 from the machine, natural, and organizational intelligence to 138
 social intelligence in the horizontal scopes and from the logical, 139
 functional, and cognitive models to neural (biological) models 140
 in the vertical reductive hierarchy. Therefore, cybernetics in 141
 nature is a multidisciplinary and transdisciplinary inquiry of 142
 cognitive information processing and autonomic systems. 143

As shown in Fig. 1, the double arrows indicate abstraction/ 144
 reduction or aggregation/specification. The scope of contempo- 145
 rary cybernetics in the horizontal domains has been extended 146
 from mainly machine intelligence to natural, organizational, 147
 and societal intelligence. In the vertical dimension, the reduc- 148
 tion levels of cybernetics have been extended from logical and 149
 functional models to cognitive and neural models. 150

With the notion of *functional reductionism*, a logical model 151
 of the NI is needed to explain formally the high-level mecha- 152
 nisms of the brain on the basis of observations at the biological 153
 and physiological levels. The logical model of the brain is 154
 the highest level of abstraction for explaining its cognitive 155
 mechanisms. Based on it, a systematical reduction from the 156
 logical, functional, physiological, and biological levels may be 157
 established in both the top-down and bottom-up approaches, 158
 which will enable the establishment of a coherent theory of NI 159
 and cybernetics. 160

It is noteworthy that, at the overall level, contemporary 161
 cybernetics has evolved from pure autonomic communica- 162
 tion and control theories to CI [44], [45] and computa- 163
 tional intelligence [22]. The former provides an extended NI 164
 and internal information-processing perspective to cybernetics, 165
 while the latter studies a computation modeling perspective to 166
 cybernetics. 167

B. Behavioral Spaces of Cybernetics

168

Behaviorism is a doctrine of psychology and CI that studies 169
 the association between a given stimulus and an observed 170
 response of human brains and cybernetic systems [45], [52]. 171
 CI reveals that human and machine behaviors may be classi- 172
 fied into four categories known as the *perceptive, cognitive,* 173
instructive, and *reflective* behaviors [46]. 174

The behavioral space of cybernetics and cybernetic systems 175
 can be classified into the imperative, autonomic, and cognitive 176
 cyberspaces (CSs), as shown in Fig. 2. The *imperative CS* is 177
 an enclosure of instructive and passive behaviors. The *auto-* 178
nomic CS is an enclosure of internally motivated behaviors 179
 beyond those of the imperative space. The *cognitive CS* is an 180
 enclosure of perceptive and inference-driven behaviors beyond 181
 those of both imperative and autonomic spaces. More formal 182
 descriptions of the three forms of CSs will be presented in 183
 Section II-B2, after each layer of the hierarchical CSs and their 184
 basic properties is formally modeled as follows. 185

1) *Behavioral Models of Cybernetics:* Before the elabora- 186
 tion of the behavioral spaces of cybernetics, the taxonomies of 187
 cybernetic behaviors at different layers of cybernetics, as shown 188
 in Fig. 2, are formally modeled in the following. 189

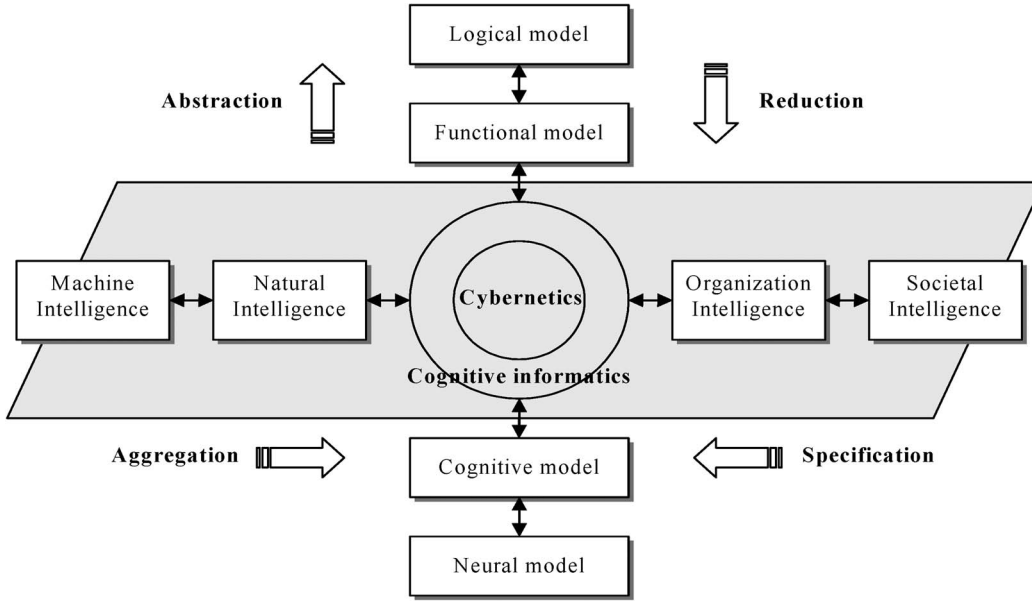


Fig. 1. Architecture of contemporary cybernetics and CI.

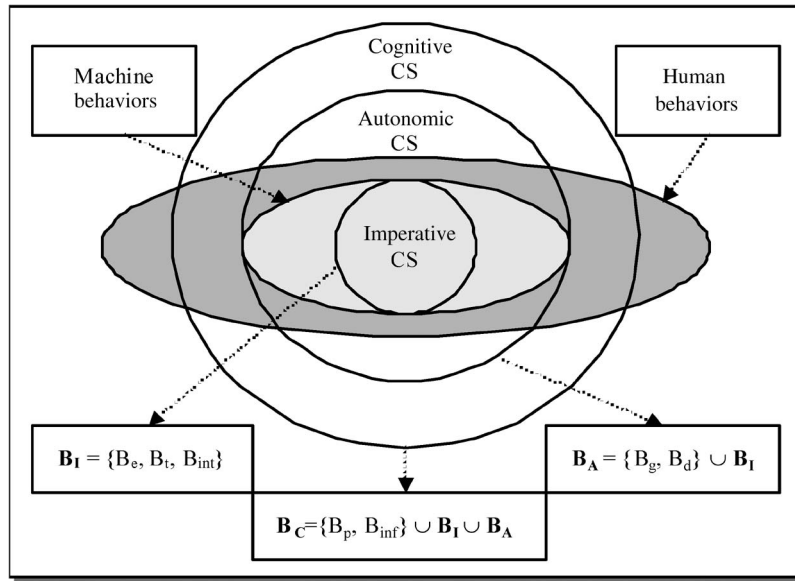


Fig. 2. Behavioral spaces of cybernetics.

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

194 The types of events that may trigger a behavior can be
 195 classified into operational ($@eS$), time ($@tTM$), and interrupt
 196 ($@int \odot$) events, where $@$ is the *event prefix*, and S , TM , and
 197 \odot are three of the type suffixes, respectively. The *interrupt*
 198 *event* is a kind of special event that models the interruption
 199 of an executing process, the temporal handover of controls to
 200 an interrupt service routine, and the return of control after its
 201 completion.

202 *Definition 3:* An *interrupt*, which is denoted by \downarrow , is a paral-
 203 lel process relation in which a running process P is temporarily
 204 held by another higher-priority process Q via an interrupt
 205 event ($@int \odot$) at the interrupt point \odot , and the interrupted

process will be resumed when the high-priority process has
 206 been completed, i.e.,
 207

$$P \downarrow Q \stackrel{\wedge}{=} P \parallel (@int \odot \nearrow Q \searrow \odot) \quad (1)$$

where \nearrow and \searrow denote an *interrupt service* and an *interrupt*
 208 *return*, respectively.
 209

In general, all types of events, including the operational,
 210 timing, and interrupt events, are captured by the system to
 211 dispatch a designated behavior.
 212

Definition 4: An *event-driven behavior* B_e , which is denoted
 213 by \hookrightarrow_e , is an imperative process in which the i th behavior in
 214 terms of a designated process P_i is triggered by a predefined
 215 event $@e_i S$, i.e.,
 216

$$B_e \stackrel{\wedge}{=} \bigwedge_{i=1}^n (@e_i S \hookrightarrow_e P_i) \quad (2)$$

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

220 *Definition 5:* A time-driven behavior B_t , which is denoted
221 by \leftarrow_t , is an imperative process in which the i th behavior in
222 terms of process P_i is triggered by a predefined point of time
223 $@t_i\mathbf{TM}$, i.e.,

$$B_t \triangleq \bigwedge_{i=1}^n \mathbf{R} (@t_i\mathbf{TM} \leftarrow_t P_i) \quad (3)$$

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

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

$$B_{\text{int}} \triangleq \bigwedge_{i=1}^n \mathbf{R} (@int_i \odot \leftarrow_{\text{int}} P_i). \quad (4)$$

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

$$B_g \triangleq \bigwedge_{i=1}^n \mathbf{R} (@g_i\mathbf{ST} \leftarrow_g P_i). \quad (5)$$

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

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

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

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

240 *Definition 9:* A decision-driven behavior B_d , which is de-
241 noted by \leftarrow_d , is an autonomic process in which the i th behavior
242 in terms of process P_i is generated by a given decision $@d_i\mathbf{ST}$,
243 i.e.,

$$B_d \triangleq \bigwedge_{i=1}^n \mathbf{R} (@d_i\mathbf{ST} \leftarrow_d P_i). \quad (7)$$

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

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

$$\begin{aligned} d &= f(\mathcal{A}, C) \\ &= f : \mathcal{A} \times C \rightarrow \mathcal{A}, \quad \mathcal{A} \neq \emptyset. \end{aligned} \quad (8)$$

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

$$B_p \triangleq \bigwedge_{i=1}^n \mathbf{R} (@p_i\mathbf{PC} \leftarrow_p P_i) \quad (9)$$

253 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 \leftarrow_{inf} , is a cognitive process in which the i th behavior
in terms of process P_i is generated by the result of an inference
process $@inf_i\mathbf{PC}$, i.e.,

$$B_{\text{inf}} \triangleq \bigwedge_{i=1}^n \mathbf{R} (@inf_i\mathbf{PC} \leftarrow_{\text{inf}} P_i) \quad (10)$$

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 cog-
nitive 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 hierar-
chy 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 be-
haviors, such as those of perception and inference in both
intelligent cybernetic systems and the brain.

Definition 13: The *imperative behavioral space* of cybernet-
ics 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.,

$$B_I \triangleq \{B_e, B_t, B_{\text{int}}\}. \quad (11)$$

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 cyber-
netics 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.,

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

An autonomic system implemented on B_A extends the pas-
sive and imperative cybernetic system on B_I to nondetermin-
istic, 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

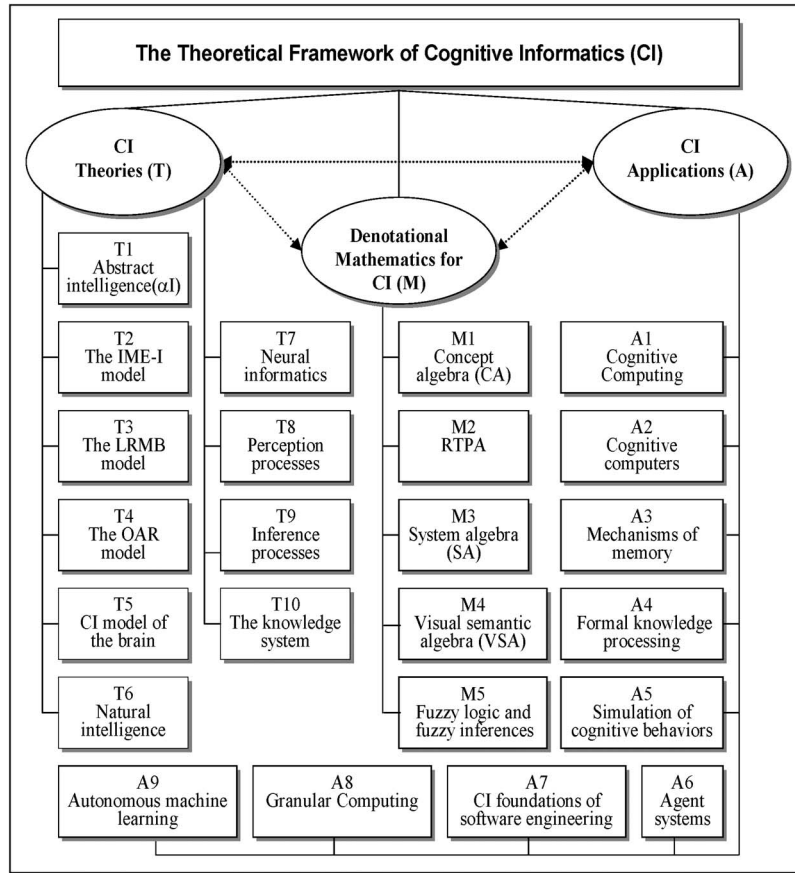


Fig. 3. Theoretical framework of CI.

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

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

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

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

III. CI FACET OF CYBERNETICS

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

Definition 16: CI is a transdisciplinary inquiry of cyber- 324
netics, cognitive science, computer science, and information 325
sciences that investigates into the internal information process- 326
ing mechanisms and processes of the brain and NI, and their 327
engineering applications via an interdisciplinary approach. 328

A. Theoretical Framework of CI

329

The structure of the theoretical framework of CI [44] is 330
shown in Fig. 3, which covers ten fundamental theories such 331
as *abstract intelligence* [51], the *information–matter–energy–* 332
intelligence (IME-I) model, the LRMB, the *object–attribute–* 333
relation (OAR) model of internal information representation 334
in the brain, the CI model (CIM) of the brain, the mechanism 335
of NI, neural informatics, the mechanism of human perception 336
processes, the cognitive processes of formal inferences, and the 337
formal knowledge system. 338

Four forms of denotational mathematics [46]–[50], such as 339
concept algebra, *real-time process algebra (RTPA)*, *system* 340
algebra, and *visual semantic algebra* are created in CI, 341
which enable a rigorous treatment of knowledge and behavior 342
representations and manipulations in a formal and coherent 343
framework. The new structures of denotational mathematics 344
have extended the abstract objects that are under study in 345
mathematics to a higher level, encompassing abstract concepts, 346
behavioral processes, abstract systems, and visual semantic 347
patterns beyond conventional mathematical entities such as 348
numbers, sets, relations, functions, lattices, and groups. 349

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

350 A wide range of applications of the descriptive mathematics
351 in the context of CI have been identified, as shown in Fig. 3,
352 particularly the cognitive computing methodologies and cogni-
353 tive computer systems [24], [44], [45], mechanisms of human
354 memory, simulation of the cognitive behaviors of the brain,
355 autonomous agent systems, CI foundations of software engi-
356 neering, granular computing [28], [34], [35], [37], [53], [61]–
357 [63], and autonomous machine learning. The latest advances in
358 CI have led to the development of cognitive computers, which
359 extends computing techniques from imperative to cognitive
360 computing that implements higher-level computing behaviors
361 in the cognitive CS, as given in Definition 15.

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

375 B. Taxonomy of Cognitive Information in the Brain

376 Almost all modern disciplines of science and engineering
377 deal with information and knowledge. However, data, informa-
378 tion, and knowledge are conventionally considered as different
379 entities in the literature [7], [60]. Based on the investigations
380 in CI, particularly the research on the OAR model [44] and the
381 mechanisms of internal information representation, the empiri-
382 cal classification of data, information, and knowledge may be
383 revised. A CI theory on the relationship among data (sensa-
384 tional inputs), actions (behavioral outputs), and their internal
385 representations such as knowledge, experience, and skill is that
386 they are generally different forms of information. These forms
387 of cognitive information may be classified based on how the
388 internal information relates to the inputs and outputs (I/O) of
389 the brain, as shown in Table I, which is known as the CIM.

390 According to the CIM, the taxonomy of cognitive infor-
391 mation is determined by types of I/O of information to and
392 from the brain, where both I/O can either be information or
393 action. For a given cognitive process, if both I/O are abstract
394 information, the internal information acquired is *knowledge*,
395 if both I/O are empirical actions, the type of internal in-

formation is *skill*, and the remainder combinations between 396
action/information and information/action produce *experience* 397
and *behaviors*, respectively. In Table I, behavior is a new 398
type of cognitive information modeled inside the brain, which 399
embodies an abstract input to an observable behavioral output. 400

Definition 17: The generic forms of cognitive information 401
state that there are four categories of internal information \mathcal{I} in 402
the brain known as *knowledge* (K), *behaviors* (B), *experience* 403
(E), and *skills* (S), i.e., 404

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

It is noteworthy that the approaches to acquire 405
knowledge/behavior and experience/skills are fundamentally 406
different. Although knowledge or behaviors may directly 407
and indirectly be acquired, skills and experiences can only 408
be obtained directly by hands-on activities. Furthermore, the 409
associated memories of the abstract information are different, 410
where knowledge and experience are retained as abstract 411
relations in long-term memory (LTM), while behaviors and 412
skills are retained as wired neural connections in action buffer 413
memory (ABM) [44]. 414

C. Behavioral Model of Cybernetic Systems 415

The basic architecture of a generic cybernetic system can 416
be refined by the behavioral models developed in Section II, 417
which evolves cybernetic technologies from the imperative 418
and autonomic behaviors to the cognitive behaviors, as shown 419
in Fig. 2. 420

Definition 18: The entire behavior space of cybernetics 421
 B_{CC} is a layered hierarchical structure that encompasses the 422
imperative B_I , autonomic B_A , and cognitive B_C spaces from 423
the bottom up, i.e., 424

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

On the basis of Definition 18, a generic cybernetic system on 425
the cognitive cybernetic space may be rigorously modeled as 426
shown in Fig. 4. The *behavioral model* of a generic cybernetic 427
system \S_{CS} is an abstract logical model denoted by a set of par- 428
allel cognitive computing architectures and behaviors, where $\|$ 429
denotes the parallel relation between given components of the 430
system. The cybernetic system is logically abstracted as a set of 431
process behaviors and underlying architectures and resources, 432
such as memory, ports, system clock, system variables, and 433
states. A cybernetic system's behavior in terms of a set of 434
processes P_i is controlled and dispatched by the system \S_{CS} , 435
which is triggered by various external or system events and 436
needs, such as interrupts, goals, decisions, perceptions, and 437
inferences. 438

Corollary 1: The three layers of the behavioral spaces B_I , 439
 B_A , and B_C obey the following relations: 440

$$B_I \subseteq B_A \subseteq B_C. \quad (16)$$

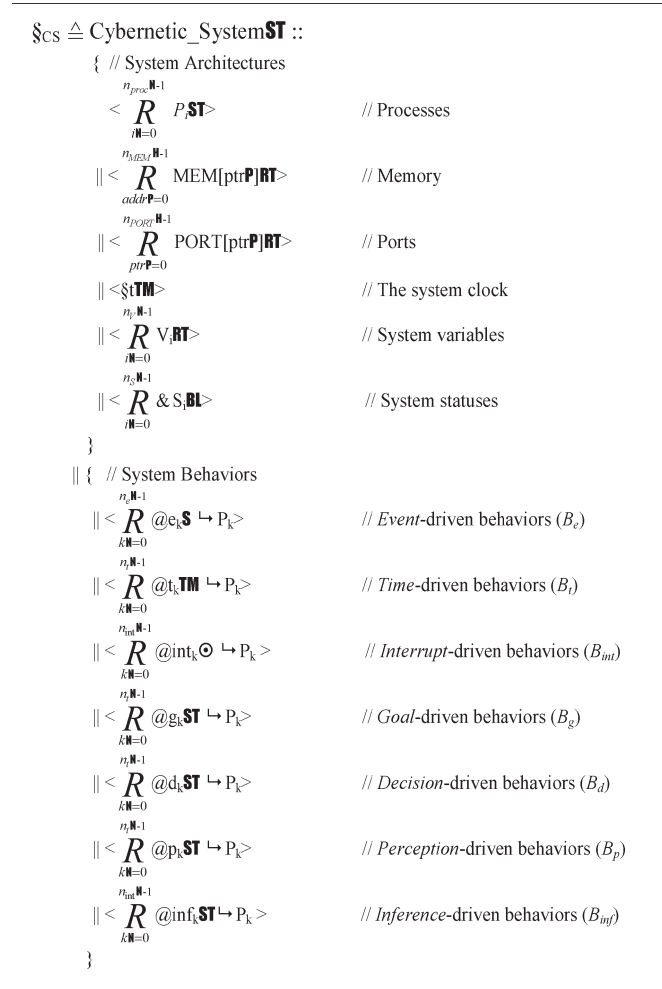


Fig. 4. Behavioral model of cybernetic systems.

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 (J) 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 cy-

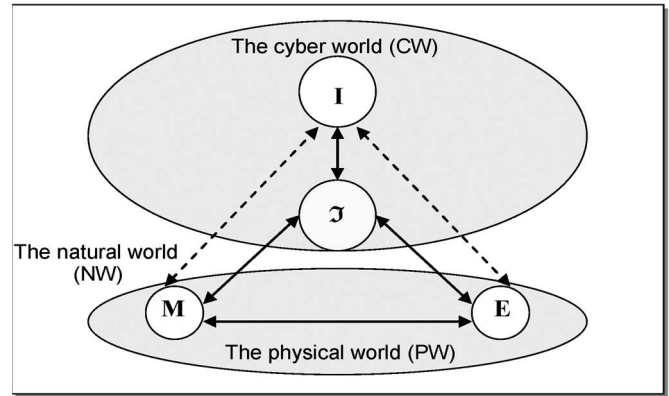


Fig. 5. IME-I model of cybernetics.

bernetics, is a dual. One aspect of it is the PW, and the other is the CW, where intelligence (J) plays a central role in the transformation between I–M–E.

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 evolutionary 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 (J) 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

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

509 IV. COMPUTATIONAL INTELLIGENCE 510 FACET OF CYBERNETICS

511 *Definition 21:* Computational intelligence is a branch of
512 cybernetics and AI that models human intelligence by compu-
513 tational methodologies and cognitively inspired models.

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

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

527 A. GIM for Cybernetics

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

535 *Definition 22:* Intelligence, in the *narrow sense*, is a human
536 or system ability that transforms information into behaviors,
537 and in the *broad sense*, it is any human or system ability that au-
538 tonomously transfers the forms of abstract information between
539 *data*, *information*, *knowledge*, and *behaviors* in the brain.

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

545 The mechanisms of the NI can be described by a GIM
546 as shown in Fig. 6. In the GIM model, different forms of
547 intelligence are described as a driving force that transfers
548 between a pair of abstract objects in the brain such as data
549 (D), information (I), knowledge (K), and behavior (B). In the

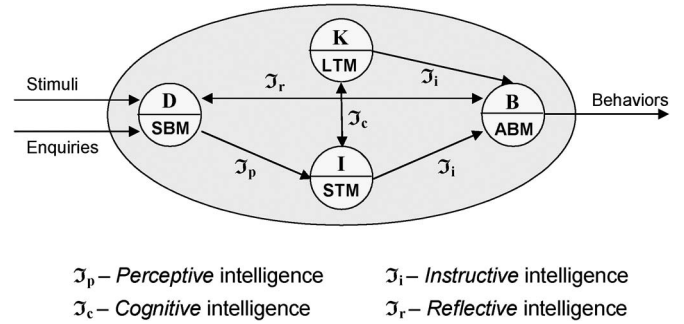


Fig. 6. GIM.

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.

Definition 23: The nature of intelligence states that intelli-
gence \mathcal{I} can be classified into four forms called *perceptive in-*
telligence \mathcal{J}_p , *cognitive intelligence* \mathcal{J}_c , *instructive intelligence*
 \mathcal{J}_i , and *reflective intelligence* \mathcal{J}_r , as modeled by

$$\begin{aligned} \mathfrak{S} &\triangleq \mathfrak{S}_p : D \rightarrow I \text{ (Perceptive)} \\ &\|\mathfrak{S}_c : I \rightarrow K \text{ (Cognitive)} \\ &\|\mathfrak{S}_i : I \rightarrow B \text{ (Instructive)} \\ &\|\mathfrak{S}_r : D \rightarrow B \text{ (Reflective)}. \end{aligned} \quad (17)$$

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.,

$$\begin{aligned} D &\triangleq r_d : M \rightarrow S_k \\ &= \log_k M, \quad k_{\min} = 2 \end{aligned} \quad (18)$$

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.,

$$I \triangleq r_i : D \rightarrow C, \quad r_i \in \mathfrak{R} \quad (19)$$

where \mathfrak{R} 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.,

$$c \triangleq (O, A, R^c, R^i, R^o) \quad (20)$$

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

578 O nonempty set of objects of the concept $O =$
579 $\{o_1, o_2, \dots, o_m\} \subseteq \mathfrak{P}U$, where $\mathfrak{P}U$ denotes
580 a power set of the universal set U ;
581 A nonempty set of attributes $A = \{a_1, a_2, \dots,$
582 $a_n\} \subseteq \mathfrak{P}M$, where M is the universal set of
583 attributes of U ;
584 $R^c \subseteq O \times A$ set of internal relations;
585 $R^i \subseteq A' \times A$ set of input relations, where $A' \sqsubseteq C' \wedge A \sqsubseteq$
586 c , and C' is a set of external concepts $C' \sqsubseteq$
587 Θ_C . For convenience, $R^i = A' \times A$ may
588 simply be denoted as $R^i = C' \times c$;
589 $R^o \subseteq c \times C'$ set of output relations.

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

$$K \triangleq r_k : C_0 \rightarrow \left(\bigtimes_{i=1}^n C_i \right), \quad r_k \in \mathfrak{R} \quad (21)$$

593 where $\mathfrak{R} = \{\Rightarrow, \overset{\pm}{\Rightarrow}, \Rightarrow, \Rightarrow, \uplus, \upharpoonright, \Leftarrow, \vdash, \rightarrow\}$ [46].

594 *Definition 28:* The *entire knowledge* \mathfrak{K} is represented by a
595 *concept network*, which is a hierarchical network of concepts
596 interlinked by the set of nine compositional operations \mathfrak{R} de-
597 fined in concept algebra, i.e.,

$$\mathfrak{K} = \mathfrak{R} : \bigtimes_{i=1}^n C_i \rightarrow \bigtimes_{j=1}^n C_j. \quad (22)$$

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

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

601 where M is generated by external stimuli or events and/or inter-
602 nal emotions or willingness, which are collectively represented
603 by a set of events $E = \{e_1, e_2, \dots, e_m\}$.

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

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

613 B. Compatibility of Natural and Machine Intelligence

614 Cybernetics and CI reveals the equivalence and compatibility
615 between NI and AI. It is rational to perceive that NI should be
616 well understood before AI may be studied on a rigorous basis.
617 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. 618 619

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. 620 621 622 623

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., 624 625 626

$$\text{AI} \cong \text{NI}. \quad (24)$$

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. 627 628 629 630

Corollary 3: The *inclusive intelligent capability* states that
AI is a subset of NI, i.e., 631 632 633

$$\text{AI} \subseteq \text{NI}. \quad (25)$$

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 com-
puter 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. 634 635 636 637 638 639 640

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. 641 642 643 644 645 646 647 648 649 650

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. 651 652 653 654

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. 655 656 657 658 659

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 infer-
ences in the future-generation intelligent computers known as
cognitive computers based on the improved understanding of
the mechanisms of NI in cybernetics and CI. 660 661 662 663 664 665 666 667 668

669

V. CONCLUSION

670 This paper has explored the architecture, theoretical foun-
 671 dations, and engineering paradigms of contemporary cyber-
 672 netics. Two cutting-edge facets of cybernetics known as CI
 673 and computational intelligence have been introduced in the
 674 cybernetic context. The GIM that provides a foundation to
 675 explain the mechanisms of the *perceptive, cognitive, instruc-*
 676 *tive, and reflective intelligence* in cybernetics has been formally
 677 developed. It has been recognized that *abstract intelligence*, in
 678 the *narrow sense*, is a human or system ability that transfers
 679 information into behaviors, and in the *broad sense*, it is any
 680 human or system ability that autonomously transfers the forms
 681 of abstract information between *data, information, knowledge,*
 682 and *behaviors* in the brain. Based on the cybernetic models, a
 683 systematical reduction from the logical, functional, physiologi-
 684 cal, and biological levels has been delineated to form a coherent
 685 theory for the studies on natural and machine intelligence in
 686 cybernetics.

687

ACKNOWLEDGMENT

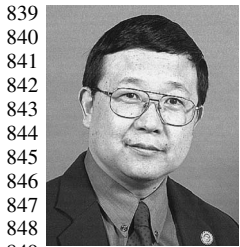
688 The authors would like to thank the anonymous reviewers for
 689 their valuable comments and suggestions.

690

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