

## Complex Intelligent Systems: Juxtaposition of Foundational Notions and a Research Agenda\*

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**Abstract:** The cardinality of the class,  $C$ , of complex intelligent systems, i.e., systems of intelligent systems and their resources, is steadily increasing. Such an increase, whether designed, sometimes changes significantly and fundamentally, the structure of  $C$ . Recently, the study of members of  $C$  and its structure comes under a variety of multidisciplinary headings the most prominent of which include General Systems Theory, Complexity Science, Artificial Life, and Cybernetics. Their common characteristic is the quest for a unified theory of a certain class of systems like a living system or an organisation. So far, the only candidate for a general theory of intelligent systems is Newell's Soar. To my knowledge there is presently no candidate theory of  $C$  except Newell's claimed extensibility of Soar. This paper juxtaposes the elements of Newell's conceptual basis with those of an alternative conceptual framework based on the thesis that communication and

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understanding are the primary processes shaping the structure of  $C$  and its members. It is patently obvious that a research agenda for the study of  $C$  can be extremely varied and long. The third section of this paper presents a highly selective research agenda that *aims to provoke* discussion among complexity theory scientists.

**Keywords:** communication, understanding, non-linear dynamical systems, complexity, intelligence, system, representation, meaning, design.

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## 1. Backdrop remarks

‘Complex’, ‘intelligent’, ‘systems’. All three labels lack specific referents. In a recent textbook by Skyttner [1], seven definitions of ‘system’ are given. The state of the art with respect to ‘complex’ is comparable (see, for instance [2-4]). With respect to ‘intelligence’ ambiguity and proliferation of theories is even worse. In AI and the psychology of human intelligence at least seven main types of theories may be found: genetic-epistemological with Piaget as the principal proponent [5]; physiological, for example, Hebb [6]; factorial, for example, Guilford [7]; information processing based, for example, Hunt [8]; logical with Nilsson as its principal proponent [9]; connectionist, for example, Rumelhart, Hinton and McClelland [10]; and functional, for example, Chandrasekaran [11]. This is hardly surprising given the far greater ‘complexity’ entailed by the term ‘intelligence’.

Complementary to such a proliferation is the quest for unification. See for example Hofkirchner's edited collection [12]. In the 20<sup>th</sup> century, in the area of our present concern, this quest started with the publication of Wiener's *Cybernetics: or control and communication in the animal and the machine* [13]. Before that the concept of system, from the perspective of the social sciences, had already been introduced and clarified by the work of Pareto [14] and Parsons [15] respectively. Presently, this quest is continued under the name of complexity theory -sometimes known as theory of complex systems or Complexity Science [3].

From the proliferation perspective, complexity theory should be understood as the set of concepts, hypotheses, and techniques that have been developed from the time of the gestalt paradigm in psychology until now aiming to discover and understand the principles of complex systems. As such it is not concerned with the peculiarities of a particular type of complex system like a human, or an organisation. From the quest perspective, complexity theory includes, and attempts to integrate, all generic approaches to the study of complex systems. Currently, the major among these are (cf. [16-17]): holism, cybernetics, general systems theory, nonequilibrium thermodynamics, chaos theory, adaptive systems, autopoietical system theory, cellular automata, Artificial Life (e.g., [18-19]) and genetic algorithms. The next section looks at two specific attempts towards unification aiming primarily to initiate a much needed discussion on such a quest.

## 2. Juxtaposition of Foundational notions

“We have then, in the current industrial revolution with information at its core, a source of great technical and social change with which we need to come to terms. But to do so entails exploring and clarifying a set of concepts and activities which are currently both confused and confusing.” Checkland and Howell [20].

The aim of this section is to initiate a discussion on the modelling of complex intelligent systems. As such the minimal information on the ideas introduced below is offered either as a memory refresher (re, Newell’s Soar) or as an agent provocateur for some of the underlying issues. As Torr [21] put it: “the recognition that two theories contain like terms that mean different things can facilitate comparison and communication.”

Despite significant alternatives (e.g., [22]), still the most elaborately worked out proposal for a unified theory of general intelligence is presented in *Unified Theories of Cognition* [23]. He proposed Soar as a candidate architecture embodying a unified theory of both human and machine cognition. This proposal aims to provide a detailed theoretical framework for understanding cognition and its key notions are knowledge, representation, computation, symbols and architecture. Within that framework, the

notion of 'intelligence' is defined in terms of the notion of the knowledge level. Specifically: "A system is intelligent to the degree that it approximates a knowledge-level system." [23, p. 90]. Where a knowledge-level system is a system interacting with its environment through actions selected on the basis of its knowledge to attain its goals.

The fundamental, underlying, assumption of this work is the physical symbol system hypothesis of Newell and Simon [24] which has been extensively tested over the past 30 years in the field of Artificial Intelligence and in a few areas of information processing Psychology. For relevant evidence the reader is referred to [17, 25-26]. On the basis of Soar's foundational notions (see Table-1 in Appendix), Newell believes that social systems, the largest subclass of  $C$ , can be characterised "as a distributed set of intendedly rational agents." We register our dissent; a justification would be well beyond the space of this paper.

The following paragraphs provide the skeleton of an alternative conceptual framework in the form of definitions fleshing out our thesis, namely, communication and understanding are the primary processes shaping the structure of  $C$  and its members.

We define: Complex Intelligent System  $\equiv_{df}$  A system of intelligent systems and their resources. Characteristic examples of complex intelligent systems include: firms, universities, communities, governments, human-robot systems, a human and her dog. Some people may be inclined to argue that intelligence implies complexity or vice versa. This is not true. For example, a crystal is a complex system without being intelligent; and Deep Blue is intelligent without being really complex.

*On the nature of intelligence:*

A system,  $S$ , is intelligent if and only if it:

- a) possesses sensors.
- b) is able to act on its environment.
- c) possesses its *own* representational system  $R_s$ , i.e.,  $R_s$  is independent of the language of another kind of entity  $S^*$ .
- d) is able to connect sensory, representational, and motor information.
- e) is able to communicate with other systems within its own class.

Remark: A system,  $S$ , is human –level intelligent if and only if it is intelligent and it is able to communicate in a human-equivalent language.

*On the nature of representation, thinking, and meaning:*

$R_e$  –symbol for the representational system of entity E.

$R_e =_{df}$  is a thought system of E able to create representations. Where: a representation of a situation, say,  $S_1$ , is another situation, say,  $S_2$ , characterised by the properties:

$S_2$  simplifies  $S_1$ ; and

$S_2$  preserves the essential characteristics of  $S_1$ .

Thought system of E =  $_{df}$  a system of thoughts of entity E.

Human thought =  $_{df}$  An ordered n-tuple of human meanings.

Definition of human meanings:

The meaning M of a linguistic expression l, in the context  $C_1$ , for the entity H, at time t -symbol M (l,  $C_1$ , H, t)- is the *prevailed* neural formations of H, at t. -symbol  $C_{bp}$ . This definition has been generalised to:

The meaning M of something s, in the context  $C_s$ , for the entity E, at time t -symbol M (s,  $C_s$ , E, t)- is the *prevailed* formations of the representational material of E, at t. -symbol  $C_{mp}$ .

The last two and the next two definitions, constituting part of our research programme on the foundations of complex intelligent systems, have been defined, justified and applied in Gelepithis [27-34].

*On the nature of communication and understanding:*

Definition of communication:  $H_1$  communicates with  $H_2$  on a topic T if, and only if: (i)  $H_1$  understands T {Symbol: U ( $H_1$  T)}; (ii)  $H_2$  understands T {Symbol: U ( $H_2$  T)}; (iii) U ( $H_1$  T) is describable to and understood by  $H_2$ ; and (iv) U ( $H_2$  T) is describable to and understood by  $H_1$ .

Definition of Understanding: An entity E has understood something, S, if and only if, E can describe S in terms of a system of *own* primitives (p is a primitive if and only if p's understanding is immediate).

The above definitions and their associated framework, as it has so far been developed in Gelepithis [27-34], address six of the fourteen foundational notions specified in the second column of Table-1 in the Appendix. The issues specified in the research agenda

that follows address, primarily, the notions of growth, emotion, and consciousness (including moral principles and, therefore, values).

### 3. Research Agenda

The following issues intend to initiate a discussion with a view to reach an agreement on the priorities of research in complexity theory.

- I<sub>1</sub>: The single most promising and, at the same time, most difficult research objective is to synthesise mathematical methods devised to explore complexity (for an introduction see [35]) with simulation models and an enhanced conceptual framework for the study of  $C$  and its members. Most likely, such an endeavour will require as yet untried mathematical tools and quite possibly invention of new ones.
- I<sub>2</sub>: Synthesise the objective and subjective viewpoints in the modelling of complex intelligent systems. In other words, hard and soft science; facts and values; qualities and quantities; criteria and measures of successful design or theoretical study.
- I<sub>3</sub>: In what specific sense the whole is greater than its parts. This brings in the issues of emergent properties and irreducibility (that is explanatory not constitutive reduction).
- I<sub>4</sub>: Appropriate placing of an artificial system within its sociotechnical environment requires the overcoming of the environment's resistance to change. Naturally, this is greater the more extensive and radical the changes of the structure and functioning of the environment are required to be in order to accommodate the new entrant. In other words, the consequences incorporating the new designed system in its sociotechnical environment should constitute part of the overall development process. How?
- I<sub>5</sub>: Following from the above, how can one manage the changes ensued to a system by instabilities purposefully created by an intervention (e.g., Kosovo war)? How can one avoid singularities of  $C$ ?
- I<sub>6</sub>: Classification of classes of systems, 37 different classes are introduced in [1], will enforce conceptual clarification.
- I<sub>7</sub>: A theory of  $C$  and its members requires regularities. The finding of such regularities should be a major research objective.

I<sub>8</sub>: Given that a group mind is too far from the truth to be a useful scientific approximation, how could unified theories of cognition be related to social components (e.g., values, morals) for successful modelling of groups?

I<sub>9</sub>: Discover or Design the fundamental relations among the key members of  $C$ , (i.e., the structure of  $C =$  the space of complex intelligent systems  $= S_c$ ).

I strongly believe that the study of the design, behaviour, and interactions of members of  $C$  is poised to play a significant role in the future development of both science and engineering. Furthermore, such a study requires a breadth of expertise that only interdisciplinary groups can provide. Such an endeavour is badly needed at the beginning of the *new* information age, which we are creating and which is shaping ourselves and our values and institutions.

## Appendix

The following two tables may provide some insight into Newell's framework and my research programme.

<i>According to Allen Newell [23]</i>	<i>According to P.A.M. Gelepithis</i>
1. Behaving systems,	1. Perception,
2. Knowledge,	2. Action,
3. Representation,	3. Growth (e.g., self-organisation),
4. Machine* (e.g., computation),	4. Meaning,
5. Symbol,	5. Thinking (e.g., computation),
6. Architecture,	6. Understanding,
7. Intelligence,	7. Communication,
8. Search,	8. Representation,
9. Preparation vs. deliberation*.	9. Intelligent system,
	10. Purpose (inc. expectation),
	11. Emotion,
	12. Human language,
	13. Consciousness (inc. moral principles),
	14. Beauty.

**Table-1: Foundational notions for the study of Complex Intelligent Systems.**

\*Terms from Newell [23]:

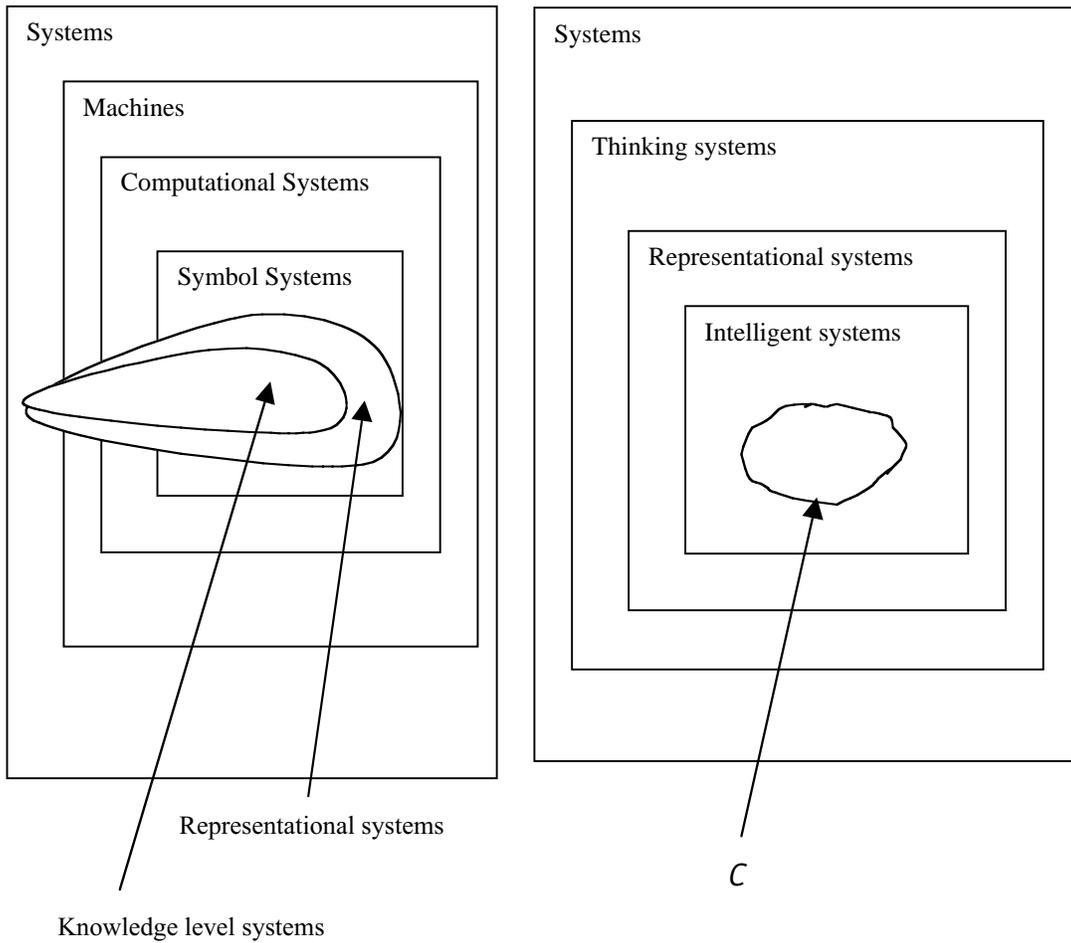
Machine: A mathematical function that produces its output given its input.

Computational system: A machine that can produce many functions.

Preparation: Knowledge encoded in a system's memory.

Deliberation: Use of knowledge to choose one operation rather than others.

Comparison of a few, but important, classes of systems (drawings are not in scale).



**Table-2: A classificatory comparison of a few basic classes of systems.**

The reader may find it interesting to compare *C* with the class of knowledge level systems.

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